Future Seismic Hazards in Southern California

Phase I:
Implications of the 1992 Landers Earthquake Sequence

U.S. DEPARTMENT OF THE INTERIOR GEOLOGICAL SURVEY

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DEPARTMENT OF CONSERVATION

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National Earthquake Prediction Evaluation Council
California Earthquake Prediction Evaluation Council
Southern California Earthquake Center

Ad Hoc Working Group
on the
Probabilities of Future Large Earthquakes
in
Southern California

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Working Group on the Probabilities of Future Large Earthquakes in Southern California

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PREFACE

This progress report addresses the implications of the 1992 Landers earthquake sequence on future seismic hazards in southern California. It represents the efforts of a joint *ad hoc* working group composed of individuals from the National Earthquake Prediction Evaluation Council (NEPEC), the California Earthquake Prediction Evaluation Council (CEPEC), and the Southern California Earthquake Center (SCEC).

Following the Landers earthquake, SCEC organized a workshop to share the preliminary results of ongoing scientific investigations. The group determined that it was necessary to address formally the implications of the Landers earthquake on seismic hazards in southern California and update earlier estimates of probabilities of large earthquakes on the region's active faults. Due to the high level of public concern, the Chairs of NEPEC and CEPEC confirmed the need for a deliberate evaluation, and a formal procedure was initiated. On August 5, 1992, NEPEC, CEPEC, SCEC, and the OES announced the formation of the joint *ad-hoc* working group composed of 12 experts to oversee the generation of a report. SCEC scientists were asked to provide the necessary technical working papers for the document. It was decided that this document should be Phase I of a two phase study of the probabilities of future large earthquakes in southern California, and should provide for the timely release of the best information available to date. A Phase II report, to be completed in about 9 months, would contain a more complete analysis of future earthquake probabilities in greater southern California.

Following review of the working papers by the *ad hoc* working group, a final version of this report was assembled by SCEC and submitted to the Directors of the USGS and OES for their approval. Since the report is the product of several different individuals working under tight time constraints, there is a degree of unevenness in style and depth of presentation.

NEPEC was established in 1979 pursuant to the National Earthquake Hazards Reduction Act of 1977 to advise the Director of the United States Geological Survey (USGS) concerning any formal predictions or other information pertinent to the potential for the occurrence of a significant earthquake.

CEPEC was formed in 1976 under existing administrative authority as the successor to an advisory group formed in 1974. CEPEC advises the Director of the California Office of Emergency Services (OES) on the validity of predictions of earthquakes capable of causing damage in California, including the reliability of the data and scientific validity of the technique used to arrive at a specific prediction.

SCEC was established by the National Science Foundation (NSF) and the USGS to integrate earth sciences research on the processes that cause earthquakes so as to improve forecasts of damaging earthquakes and their effects. A fundamental goal of SCEC is to develop a master model that will provide the basis for a time-dependent probabilistic seismic hazard analysis of southern California. SCEC is a consortium of seven research institutions in partnership with the USGS. Member institutions include the California Institute of Technology, Columbia University, the Universities of California at Los Angeles, San Diego, Santa Barbara, and Santa Cruz, and the University of Southern California -- SCEC's managing institution.

The scientific input to the present Phase I report consisted of working papers prepared by the Southern California Earthquake Center. These interim documents were an outgrowth of three workshops held on July 13, July 27 and August 24, 1992. Principal authors of the working papers were Duncan Agnew, Ruth Harris, David Jackson, Lucy Jones, Kerry Sieh, Bob Simpson, and Ross Stein. Duncan Agnew and David Jackson assembled the papers, which were organized and edited into this report by Tom Henyey, with help from Virgil Frizzell and John McRaney. In addition, the following scientists participated in the workshops and/or contributed ideas and materials to the working papers: Kei Aki, Allin Cornell, Jim Davis, Jim Dieterich, Bill Ellsworth, Jack Evernden, Egill Hauksson, Tom Heaton, Tom Henyey, Anshu Jin, Yan Kagan, Simeon Katz, Volodja Keilis-Borok, Geoff King, Volodja Kossobokov, Tanya Levshina, Allan Lindh, Mehrdad Mahdyiar, Tom McEvilly, Karen McNally, Bernard Minster, Steve Park, Paul Reasenberg, David Schwartz, Lynn Sykes, Steven Ward, Ray Weldon, and Steven Wesnousky.

TABLE OF CONTENTS

I. EXECUTIVE SUMMARY

Southern California and its seismologists received a wake-up call on June 28, 1992. The largest earthquake to strike southern California in 40 years occurred near the town of Landers, located 30 km north of the San Andreas fault. It had a magnitude of 7.5 (M7.5). Three and one-half hours later, a M6.5 aftershock struck the Big Bear area 40 km (kilometers) to the west of Landers. An *ad hoc* working group was rapidly convened in July, 1992, to evaluate how the Landers-Big Bear earthquake sequence might affect future large earthquakes along major faults in southern California. In particular, what are the chances of large earthquakes in the next few years and how do they compare to previous estimates (such as those of the Working Group on California Earthquake Probabilities -- WGCEP, 1988)? Such an evaluation was made for central California after the Loma Prieta earthquake of 1989 (WGCEP, 1990). The charge to the Landers *ad hoc* working group included analyzing the seismicity for the last several years in southern California and the new paleoseismic, geologic, and geodetic data recently available for southern California. To inform the public about the potential hazard of plausible earthquakes, the working group was also asked to map the predicted severity of ground shaking for such earthquakes compared to that from the Landers earthquake.

The following observations raise concern that a large earthquake might soon occur in southern California:

- Portions of the southern San Andreas fault appear ready for failure; where data are available, the time elapsed since the last large earthquake exceeds the long-term average recurrence interval.
- Since 1985, earthquakes have occurred at a higher rate than for the preceding four decades.
- The Landers earthquake is estimated to have increased the stress toward the failure limit on parts of the southern San Andreas fault.
- Some aftershocks of the Landers earthquake sequence occurred near the San Andreas fault; a few appeared to be within the mapped fault zone near Yucaipa. These aftershocks are in areas where, typically, the seismicity has been relatively low.

Based on discussions with some scientists, the news media have stated that the Landers earthquake belongs to a developing fault system which may be replacing the San Andreas as the boundary between the North American and Pacific plates. These statements refer to a geologic process which is taking place on a time scale of millions of years. Studies of recent geologic history and modern strain measurements, however, suggest that the well-known Mojave shear zone, in which the Landers earthquake occurred, accommodates only 15-20 percent of the total plate motion. Therefore, the San Andreas fault system, which has more than 70 percent of the plate motion, will continue to provide most major earthquakes in southern California over any human time scale.

The perception that many earthquakes have been felt in southern California lately is one reason for public concern over the Landers earthquake. This perception is accurate -- in the last 7

1/2 years (since 1985), a higher rate of earthquake occurrence has existed than for the preceding four decades (by a factor of 1.7 for M5 and above, and by a factor of 3.6 for M6 and above). We do not know, however, if this increased activity represents a departure from a lower background rate and could now be over, or if the higher rate will persist in the future.

The Landers earthquake belongs to a sequence of regional earthquakes including the 1975 Galway Lake (M5.2), 1979 Homestead Valley (M5.6), 1986 North Palm Springs (M6.0) and 1992 Joshua Tree (M6.1) earthquakes. The stress redistribution from these earlier earthquakes is estimated to have increased the stress that contributed to failure along most of the future Landers rupture by up to 1 bar (15 lbs/in^2). The Joshua Tree earthquake on April 22, 1992, occurred at the south end of the impending rupture. In early June its aftershocks began to spread northward toward the future epicenter of the Landers mainshock. In retrospect, a few of these events that occurred at the site of the Landers epicenter may be regarded as foreshocks.

The stress redistribution inferred for the Landers earthquake increased the stress toward the failure limit for some segments of the San Andreas fault (by up to 10 bars for the San Bernardino Mountains segment and less than one bar for the Coachella Valley segment), but decreased it for the Mojave segment by less than a bar. Most significantly, the Landers earthquake has been estimated to have increased the stress toward failure by about 3 bars in the rupture area of the Big Bear earthquake. We regard the M6.5 Big Bear event to be an aftershock to the Landers earthquake because it occurred shortly after Landers (3 hr 6 min later) and its distance was within one rupture length of that event.

The Landers aftershock sequence has behaved normally for a M7.5 California mainshock and such activity should continue for at least three years. Beginning September 1, 1992, there are 85 and 23 percent probabilities of M>5 and M>6 aftershocks, respectively, over the next year, and 95 and 34 percent probabilities, respectively, over the next three years. One obvious concern is that one of these aftershocks might actually turn out to be a foreshock to a large event on the San Andreas fault system. This concern was addressed by CEPEC after the Landers earthquake, and OES was advised to plan precautionary measures for a 3-day alert in case of a M6 of greater earthquake on or near the San Andreas fault.

The Landers earthquake has raised questions about the prospect for additional large (M>7) earthquakes in southern California within the next few years. The most likely case is that no large earthquake (M>7) will occur. Statistics based on global earthquake catalogs indicate that the probability of a large earthquake (M>7) following another one drops sharply after two months. If a large event should occur within 100 km of the Landers rupture in the next few years, however, it would most likely originate on one or more of the following structures:

- The Mojave shear zone. Individual fault strands include the Helendale, Lenwood-Lockhart, Old Woman Springs, northern Johnson Valley, Calico-Blackwater, Rodman-Pisgah, and/or the southern half of the Emerson fault.
- The San Bernardino Mountains and Coachella Valley segments of the San Andreas fault, or a combination of the San Bernardino Mountains segment with either the Coachella Valley segment or the Mojave segment, or with both.
- The northern San Jacinto fault.

The increase in earthquake activity since 1985, including the Landers sequence, has resulted in an increase of our estimate of the yearly probability throughout southern California. The yearly probability of a M7 or larger earthquake prior to 1985 was estimated to be about 4 percent. Now it is at least 5 percent and may be as high as 12 percent. These larger values reflect the recent increase in seismicity in southern California. This range of values allows for the effects of stress redistribution by the Landers earthquake and the ripeness for failure of the southern San Andreas fault. We estimate the probability of a large earthquake (M>7) within 100 km of the Landers rupture to be 2 to 5 percent within one year from September 1, 1992.

Ground shaking for the Landers earthquake and some of the other plausible earthquakes has been simulated using information about the earthquake source, seismic wave propagation effects, and geologic site conditions. The simulation yields a distribution of seismic intensities consistent with the observed ground motions for the Landers earthquake. The simulated high intensity for the epicentral area is consistent with the levels of damage actually experienced, and observed accelerations as high as 0.9g. Fortunately such strong shaking only occurred in sparsely populated areas. Plausible future events in the Mojave shear zone will produce effects similar to the Landers earthquake. However, such earthquakes on the San Andreas and San Jacinto faults would cause much stronger shaking in more urbanized areas. The conclusions of this report underscore the plausibility of large damaging earthquakes affecting metropolitan areas of southern California. As such, the California Office of Emergency Services should intensify its efforts to assist local governments and the public in preparing for such eventualities.

This report is intended for disaster-preparedness personnel, engineers, science writers and interested members of the public, as well as members of the earth science community. It is the first (Phase I) of two reports to be issued over the next 9 months and specifically addresses the implications of the Landers earthquakes. A second report (Phase II) will quantitatively address the more difficult problems identified in preparing this report and consider in more detail additional faults and earthquake probabilities in the broader southern California region.

II. INTRODUCTION

On the morning of June 28, 1992, most people in southern California were awakened by a very large earthquake -- the largest in California in 40 years. Named "Landers" after the small desert community near its epicenter (Figure 1), this quake had a magnitude of 7.5 (M7.5), making it the third largest in California of this century. The only larger shocks have been the 1952 Arvin-Tehachapi earthquake (M7.7) and the 1906 San Francisco earthquake (M8.3). The 1989 Loma Prieta earthquake (M7.1), while far more destructive than the Landers earthquake, released only about one-fourth the amount of energy. The sheer size of the Landers earthquake, its proximity to the southern San Andreas fault, its aftershock pattern (Figure 2a), and the fact that its sense and orientation of slip (north northwest with right-lateral strike-slip motion) were similar to that of the San Andreas, immediately raised questions. In particular, how might it be related to future earthquakes on the San Andreas proper? This report addresses these questions.

A working group on California Earthquake Probabilities (1988; henceforth referred to as WGCEP 88) determined the probabilities of large earthquakes on the major strike slip faults in California including the San Andreas, San Jacinto, Hayward, Calaveras, and Imperial faults. This group derived probability estimates based upon an interpretation of fault segmentation, patterns of historical seismicity, and an interpretation of the geologic evidence for prehistoric events (paleoseismology). One widely quoted conclusion was that a M7.5 or larger earthquake had a

Some Definitions

Fault:	A fracture in the earth's crust accompanied by a displacement of one side of the fracture with respect to the other, and in a direction parallel to the fracture. The relative displacement is the fault slip, and the extent of the fracture is the rupture length.
Earthquake:	A shaking of the earth that is tectonic or volcanic in origin. A tectonic earthquake is caused by fault slip.
Hypocenter:	The starting point of a fault rupture. Ruptures propagate away from the hypocenter at velocities of a few km/sec.
Epicenter:	The point on the earth's surface directly above the hypocenter.
Cluster:	Earthquakes tend to cluster within a space-time window. The largest earthquake of the cluster, if distinct, is called the mainshock. Those quakes preceding the mainshock are called foreshocks, and those following the mainshock are called aftershocks. If there is no distinct mainshock, the cluster is called an earthquake swarm. A foreshock that occurs outside the normal time window is called a preshock.
Hazard:	A source of danger that has the potential for creating adverse consequences.
Risk:	The likelihood of adverse consequences.
Ripeness of a fault:	Refers to the relationship between the elapsed time since the last major earthquake on a given fault and the average recurrence interval between large earthquakes on that fault. Part of the southern San Andreas fault is ripe because the time since the last earthquake actually exceeds the average time between large earthquakes (recurrence interval).
Clock advance:	Within a recurrence interval stress is believed to increase gradually with time until failure. If additional stress is imposed on the fault, failure will occur sooner, advancing the clock.

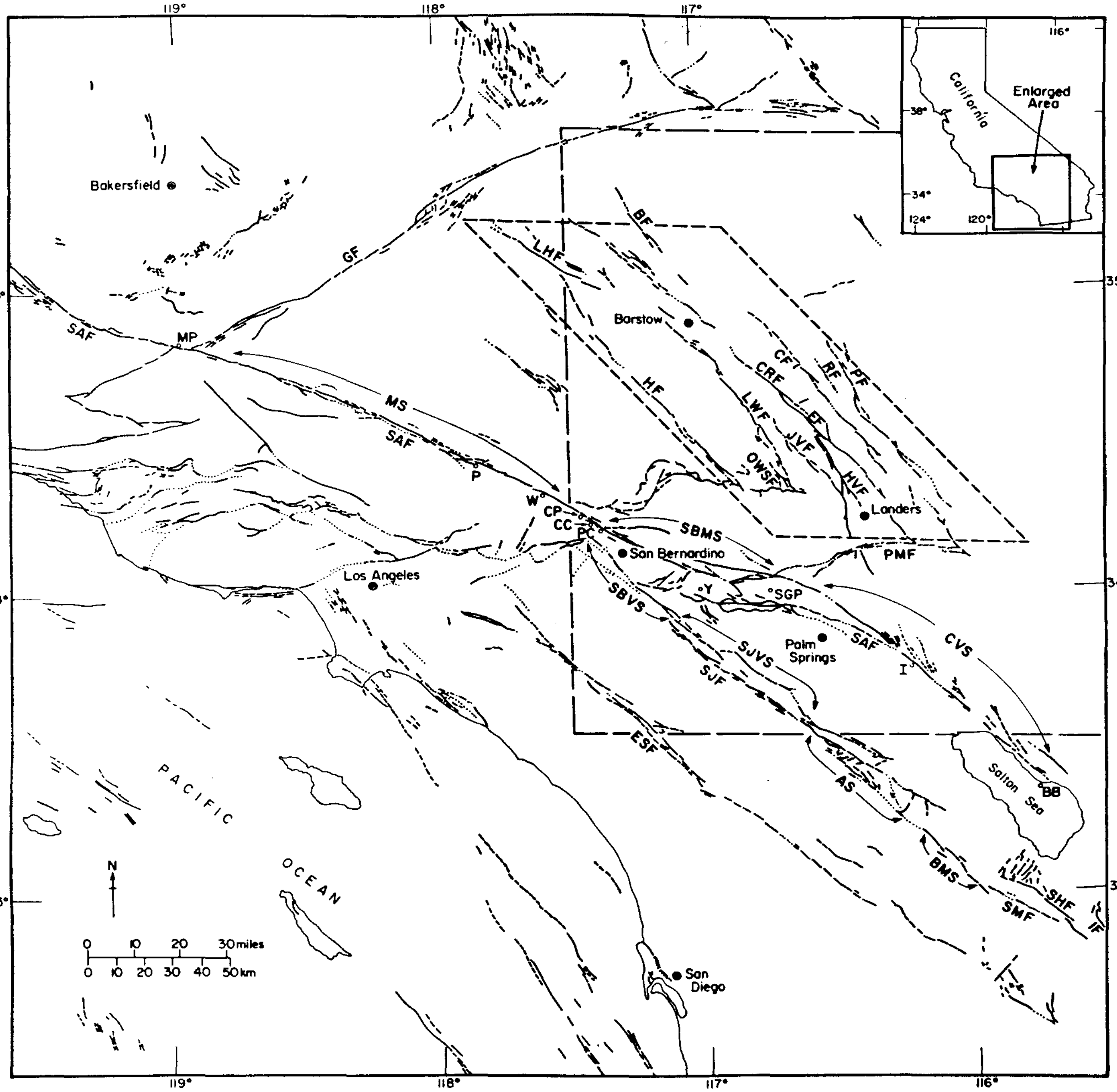

Figure 1. Map of southern California showing locations and faults (adapted from Jennings, 1992) discussed in text.

AS:	Anza segment of San Jacinto Fault.	CC:	Cajon Creek
BB:	Bombay Beach	CP:	Cajon Pass
BF:	Blackwater Fault	CF:	Calico Fault
BMS:	Borrego Mountains segment of San Jacinto Fault.	CRF:	Camp Rock Fault
C:	Carrizon	CVS:	Coachella Valley segment of San Andreas Fault.

(key continued on next page)

ESF:	Elsinore Fault	PC:	Pitman Canyon
EF:	Emerson Fault	PF:	Pisgah Fault
GF:	Garlock Fault	PMF:	Pinto Mountain Fault
HF:	Helendale Fault	RF:	Rodman Fault
HVF:	Homestead Valley Fault	SAF:	San Andreas Fault
I:	Indio	SBMS:	San Bernardino Mts segment of San Andreas Fault
IF:	Imperial Fault	SBVS:	San Bernardino Valley segment of San Jacinto Fault
JVF:	Johnson Valley Fault	SGP:	San Gorgonio Pass
LHF:	Lockhart Fault	SHF:	Superstition Hills Fault
LWF:	Lenwood Fault	SJF:	San Jacinto Fault
MP:	Mill Potrero	SJVS:	San Jacinto Valley segment
MS:	Mojave segment of San Andreas Fault	SMF:	Superstition Mountain Fault
OWSF:	Old Woman Springs Fault	W:	Wrightwood
P:	Pallet Creek	Y:	Yucaipa

The rectangular region outlined by long dashed lines is the Greater Landers Region discussed in Section VII - B. The Mojave shear zone is outlined by short dashed lines.

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60 percent probability of occurring somewhere on the southern San Andreas within the next 30 years. This conclusion assumed that the San Bernardino Mountains segment of the San Andreas could not break independently of other segments. If it could, the probability was estimated to be closer to 70 percent within 30 years. Following the 1989 Loma Prieta earthquake, a similar working group (1990; WGCEP 90) reported that the Loma Prieta earthquake increased the stress on adjacent segments of the San Andreas, thereby modestly increasing the probabilities of earthquakes there. WGCEP 90 considered new paleoseismic data for faults north of San Francisco Bay, finding that these results implied a somewhat higher risk than had been estimated in 1988. New paleoseismic data also exist for southern California and must be included in any comprehensive reevaluation of earthquake probabilities there.

This progress report analyzes how the Landers earthquake affects intermediate-term seismic hazard in southern California. Although some parts of this report are more technical than others, it does not deal with certain issues that would be detailed in a more formal scientific paper. A more thorough study (Phase II) will assess expected ground motions in the major urban areas, and more fully treat the regional effects of the Landers earthquake, the implications of the new paleoseismic data, and earthquake probabilities on major faults in a broader region of southern California. This Phase I report does not replace the 1988 and/or 1990 reports, nor does it alter their basic conclusions. Damaging earthquakes are a fact of life in California and a high probability exists for one or more within the next thirty years.

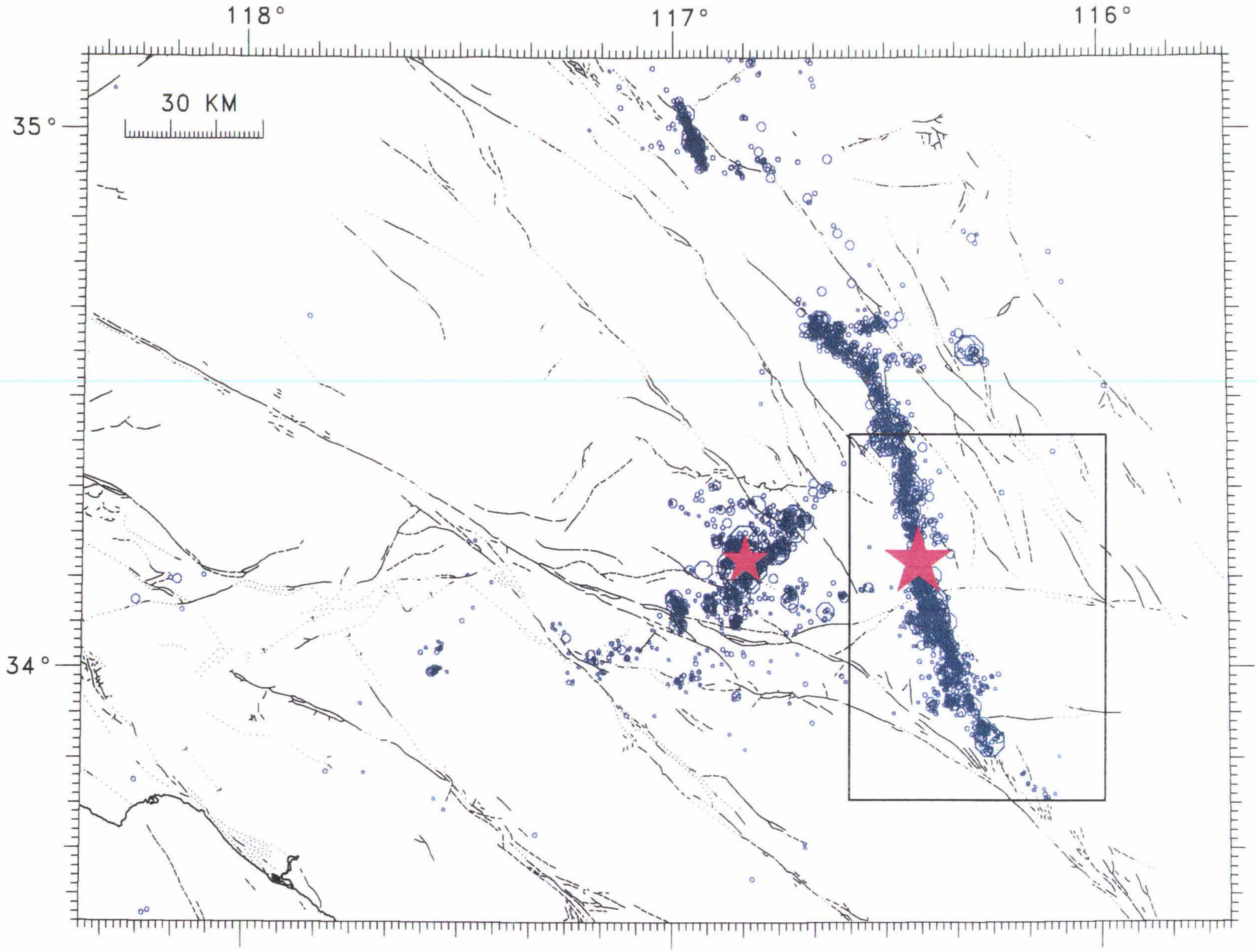


Figure 2A. Source region of the June 28, 1992, M7.5 Landers and M6.5 Big Bear earthquakes (red stars). Blue circles represent aftershocks through August 18, 1992. Size of stars and circles indicate relative strengths. Box shows location of Figure 2B.

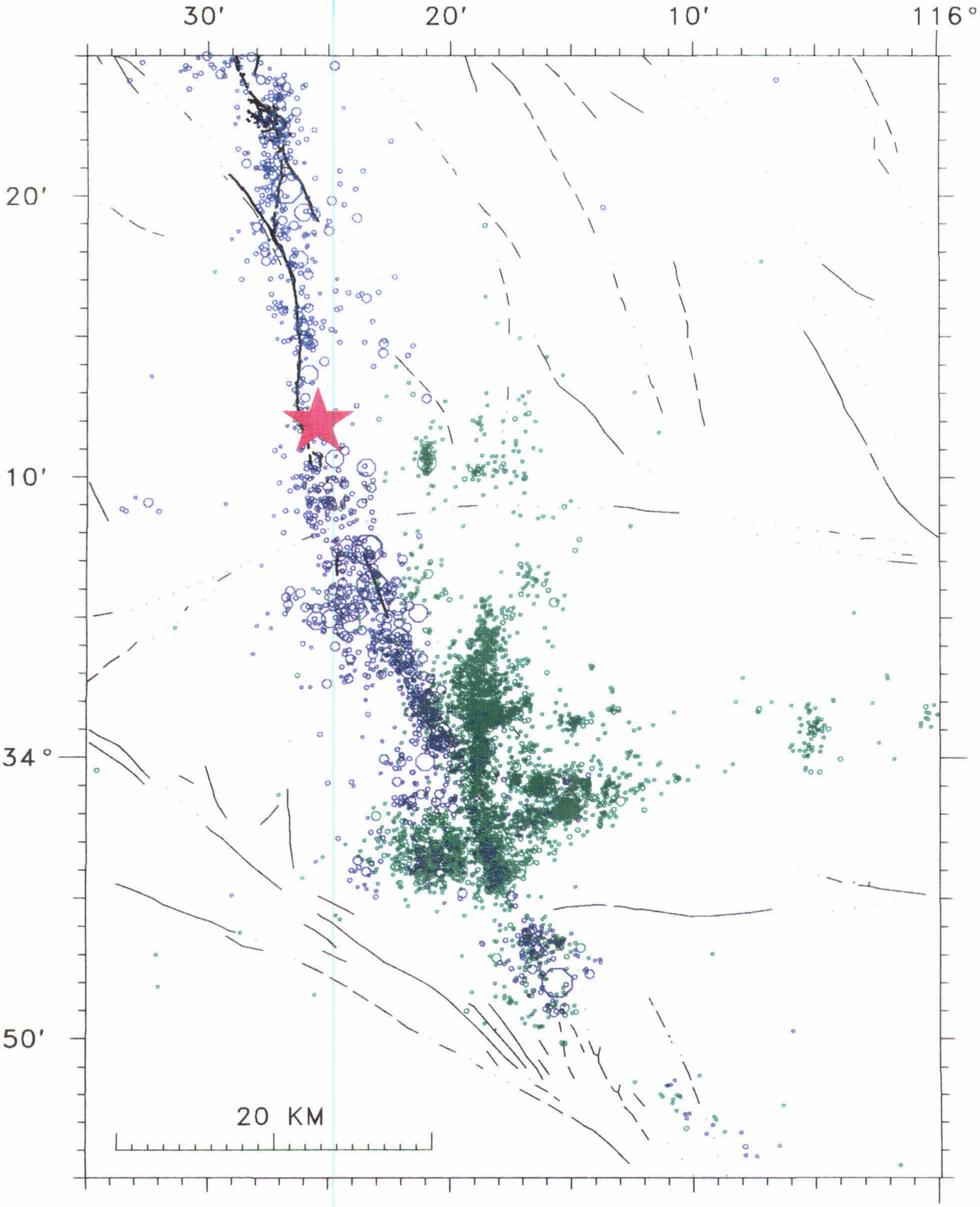


Figure 2B. Distribution of epicenters of the Landers and April 22, 1992, M6.1 Joshua Tree aftershocks. Red star is epicenter of Landers mainshock; blue circles are subsequent aftershocks. Green circles are aftershocks related to the Joshua Tree earthquake.

III. RECENT SEISMICITY

The Landers earthquake is the latest in a series of damaging earthquakes that have struck southern California over the last six years. The rate at which southern California earthquakes have been occurring, especially those of M5 and greater, has increased noticeably over the last several years. Awareness has been heightened by the number of damaging events between M5.5 and M5.9 occurring northeast of Los Angeles in the highly urbanized San Gabriel Valley. Although southern California lacks an adequate historical perspective with which to consider the significance of this increase in seismicity, it is interesting to note that in the 50 years preceding the great 1906 San Francisco earthquake, the rate of occurrence of moderate-sized earthquakes in northern California was significantly greater than for the following several decades. Other studies of seismicity patterns further suggest that earthquakes tend to cluster in space and time.

The annualized rate of earthquakes in southern California plotted by decade beginning in 1945 (Figure 3) appears to indicate an increase in the last 7.5 years. For M4.0 and above events, the rate has not changed much with time, although since 1985 the rate appears to have increased slightly over the previous two decades. However, when considering only larger earthquakes, the difference between decades appears to be greater. For M5 and above, the most recent interval has a rate 1.7 times the average of the past four decades, and for M6 and above, the rate for the last interval is 3.6 times the average of the same period (Table 1). The implications of this change will be considered in Section VII-C of this report.

Finally, a series of maps (Figure 4) show a change in the spatial distribution of earthquakes greater than M4 on a decade by decade basis. Before 1985, the San Jacinto fault, the Mojave desert, and the Imperial Valley were the sites of many shocks of M4 and larger; earthquakes of M6 and larger were rare and scattered. Since 1985, shocks of M5 and above have been concentrated in the San Gabriel Valley, along the southern San Jacinto fault, and most recently, in the Landers/Big Bear/Joshua Tree region northeast of the San Andreas fault.

IV. THE LANDERS AND BIG BEAR EARTHQUAKES

A. General Information

The Landers and Big Bear earthquakes remind us that not all large southern California earthquakes occur directly on the San Andreas fault. Thus, while the San Andreas is the most significant fault in California, earthquake preparedness must not focus solely on this fault. Although this earthquake sequence was unforeseen, it occurred on faults previously classified as active (Morton and others, 1980). The surface faulting from the Landers earthquake occurred almost entirely within one or more special studies zones (Hart and others, 1988) already delineated by the California Department of Conservation's Division of Mines and Geology under the Alquist-Priolo Special Studies Zones act for designating active faults, but the actual combination of faults along the zone of rupture was not anticipated. Most active faults in the Mojave Desert have apparently formed in the last 6 to 10 million years (Dokka, 1983), roughly the same period over which the southern San Andreas fault, the Gulf of California, and Salton Trough developed.

Table 1. Changes in Rate of Earthquakes in Southern California

Parameter	1945-1984	1985-1992
a-value (annual average for the period)	4.40	3.09
b-value (average for the period)	0.88	0.57
Annual rate, magnitude ≥ 5.0	1.0 /yr	1.7 /yr
Annual rate, magnitude ≥ 6.0	0.13/yr	0.48/yr

The a- and b-values come from the empirical Gutenberg-Richter relation, $N(M)=10^{(a-bM)}$ or $\log_{10}N(M)=a-bM$, for the number of earthquakes, N(M), above magnitude M. The a-value is a constant and a measure of the size of the population, while the b-value, also a constant, is a measure of the relative numbers of events of different magnitudes. The a- and b-values are determined from linear regression analyses of earthquake magnitude statistics.

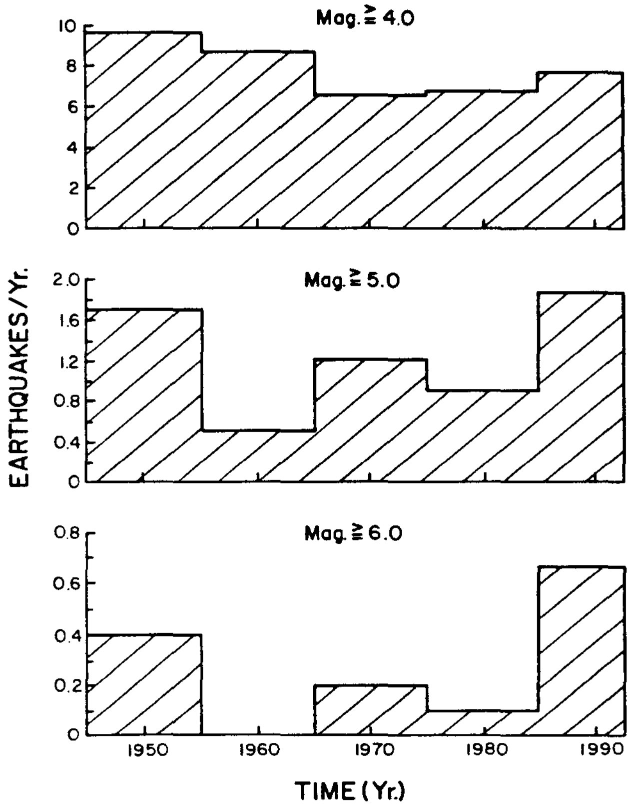


Figure 3. Annualized rate of earthquakes in southern California plotted by decade beginning in 1945. Although California Institute of Technology's Southern California Seismographic Network has recorded earthquakes since 1932, consistent determinations of magnitude to the nearest 0.1 units have been made only since 1945 (Hutton and Jones, 1992). Thus, the figure uses decade averages beginning in 1945 except for the last 7 1/2 years.

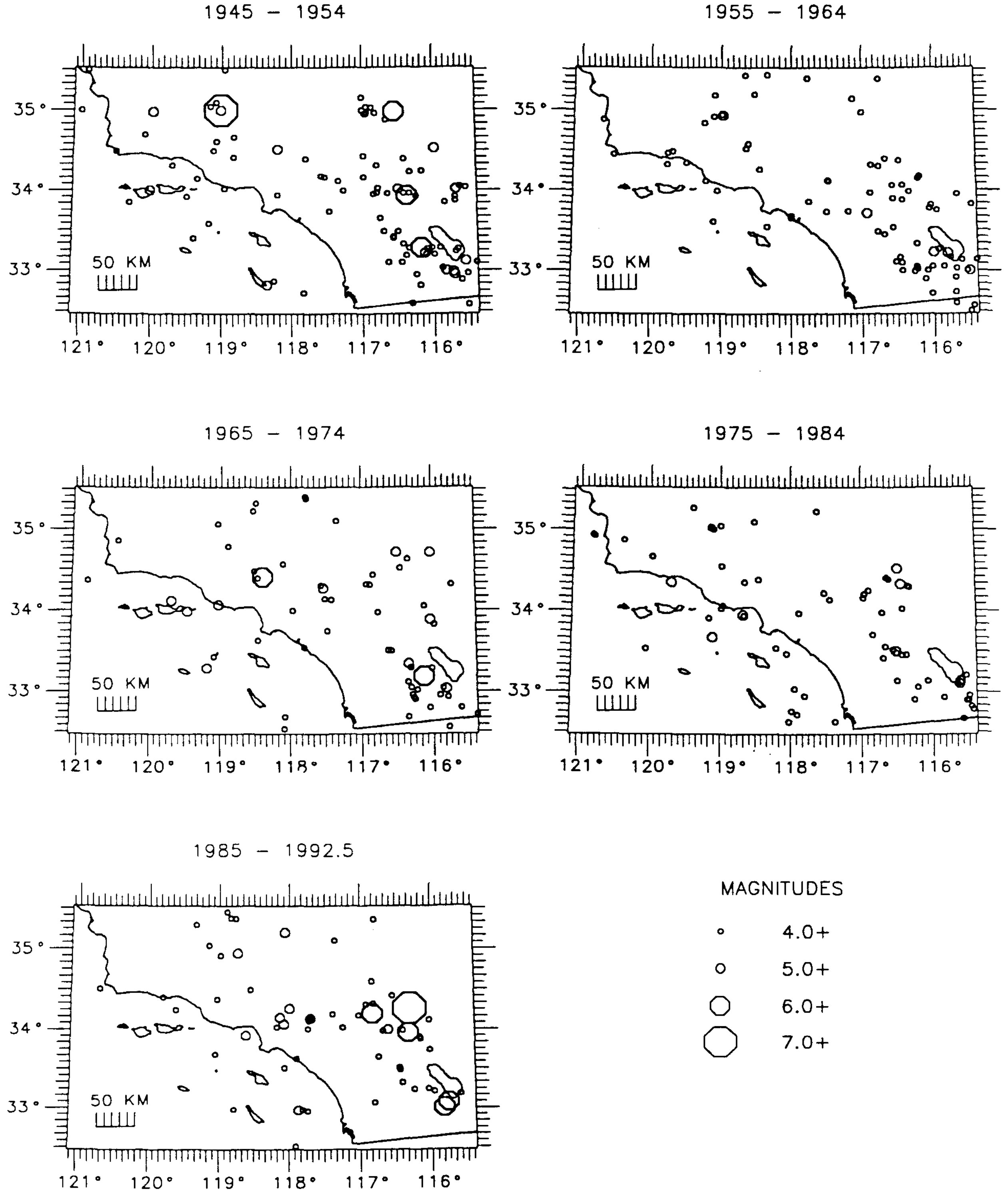


Figure 4. Epicenter locations of earthquakes of M4 and greater for the southern California region by decade from 1945 to 1985 compared with the period 1985 to 1992.

Earthquakes are driven by the tectonic stress resulting from strain accumulation in the earth's brittle upper crust. Geodetic and geologic data from the Mojave Desert had previously shown strain accumulating along a belt through which the Landers earthquake ruptured. This belt, known as the eastern California or Mojave shear zone (Figure 1), seems to average approximately 8-10 mm/yr (millimeters per year) of displacement (Savage and others, 1990; Dokka and Travis, 1990), and apparently transfers motion from the San Andreas fault in the Imperial Valley to the Basin and Range province in eastern California, Nevada, and Utah. The San Andreas system in California is responsible for approximately 35 mm/yr of displacement, with another few mm/yr offshore to make up a total of 48 mm/yr (DeMets and others, 1990) on the North American-Pacific plate boundary. Thus, the Mojave shear zone accommodates about 15-20 percent of the strain occurring along the plate boundary -- enough to be seismically active in historical time, but at a lower rate than for the main faults farther west. Over any time scale appropriate for public planning, the San Andreas and its related faults will continue to be southern California's most active fault.

In retrospect, the Landers earthquake sequence began with the M6.1 Joshua Tree earthquake of April 22, 1992. This earlier event occurred with no sign of surface faulting on an unmapped north-south fault in the westernmost part of Joshua Tree National Monument. Its aftershocks, while largely restricted to a zone between the San Andreas and Pinto Mountain faults, gradually spread northwards over the next two months. The June 28, 1992, Landers earthquake began with a rupture on the north-south trending Johnson Valley fault, which is north of the east -west trending Pinto Mountain fault and slightly offset from the trend of the Joshua Tree rupture (Figure 1). This new rupture then propagated further north, along parts of the Homestead Valley, Emerson, and Camp Rock faults, extending over 70 km to the Rodman Mountains. In addition, the aftershocks of the Landers earthquake extended from the epicenter southwards across the Pinto Mountain fault and towards the San Andreas fault. The slip averaged 3-4 m (meters) and reached a maximum of approximately 6 m in Upper Johnson Valley. Three and one-half hours after the Landers event, a fault near Big Bear slipped at roughly right angles to the Landers rupture, but did not break the earth's surface. This slip resulted in the M6.5 Big Bear earthquake. Both quakes have been followed by long trains of aftershocks typical for their size (Figure 2a). Because of the temporal and spatial proximity of the Landers and Big Bear events, we regard the latter to be an aftershock of the former. It is not unusual for the largest aftershock of a magnitude 7.5 earthquake to be of magnitude 6.5.

B. Foreshocks and Aftershocks

We consider the M6.1 Joshua Tree earthquake of April 22 to be a preshock to the Landers earthquake. Its epicenter was about 30 km south of the Landers epicenter, on the same fault system, but probably on a different fault plane. The Joshua Tree earthquake had unusually high activity aftershock sequence for a M6.1 mainshock and included about 6000 aftershocks prior to the Landers earthquake. They mostly occurred on a previously unmapped north-northwest trending fault extending from the San Andreas fault to the Pinto Mountain fault; some occurred on a few small parallel faults (Figure 2b). In early June, the Joshua Tree aftershocks began to spread north of the Pinto Mountain fault, toward the future epicenter of the Landers mainshock.

Most of these events were east of the impending Landers rupture, but in retrospect, a few were Landers foreshocks, having occurred at the site of the future Landers epicenter.

Many Joshua Tree aftershocks (Figure 2b) occurred on, and helped define the fault system responsible for the Landers mainshock -- a composite fault structure that trends north-northwest at its southern end and northwest at its northern end. These Joshua Tree events at least partially contributed to stress loading (discussed briefly below) on the eventual Landers zone. The largest aftershock to the Landers event was the Big Bear quake; this shock occurred on a separate, northeast-trending fault, located in the San Bernardino Mountains west of the Landers rupture. Additional aftershocks occurred: (a) in a patch northeast of Barstow, about 20 km north of, and on trend with the northernmost extent of the Landers rupture, and (b) in a couple of small patches east of the rupture. Although the Joshua Tree and Landers aftershocks did not cross the San Andreas fault, earthquakes following the Big Bear event occurred southwest of the San Andreas fault along the trend of the Big Bear aftershocks sequence.

The magnitude distribution and temporal pattern of aftershocks to the Landers earthquake have behaved normally for a M7.5 mainshock. Generally, the number of aftershocks in a given sequence increases exponentially with magnitude of the mainshock. Thus, there have been a great many aftershocks -- the Southern California Seismic Network recorded more than 10,000 events in the 45 days from June 28 to August 11. Given the present pattern of aftershock behavior, the aftershocks in the Landers/Big-Bear sequence will continue for at least three years.

The aftershock pattern for the Landers and Big Bear earthquakes can be used (Jones, 1992; also see Appendix) to estimate the probability of an aftershock occurring in a given magnitude range in a given time period (Table 2). The chance of more aftershocks capable of damage (M>5) over the next three years is high (95 percent). Such events pose little risk in most of the Landers rupture zone because of its low population density, but this is less true for an aftershock in the Big Bear area. Independent estimates of the probabilities for Landers and Big Bear aftershocks using the method outlined in the Appendix indicate that the Landers-only probabilities are very close to those shown in Table 2, while those for Big Bear are much smaller -- only 1 percent in the next year for a M6 or greater. This estimate is a consequence of the smaller magnitude of Big Bear's mainshock. It is probably better, however, to consider the Big Bear event and its aftershocks as a part of the Landers sequence. An extension of the Big Bear rupture in another M6 is physically plausible.

Table 2. Aftershock Probabilities for Combined Landers/Big Bear Sequence Starting September 1, 1992

Magnitude	1 yr	3 yr
>5	85%	95%
>6	23%	34%

C. Distant Triggered Earthquakes

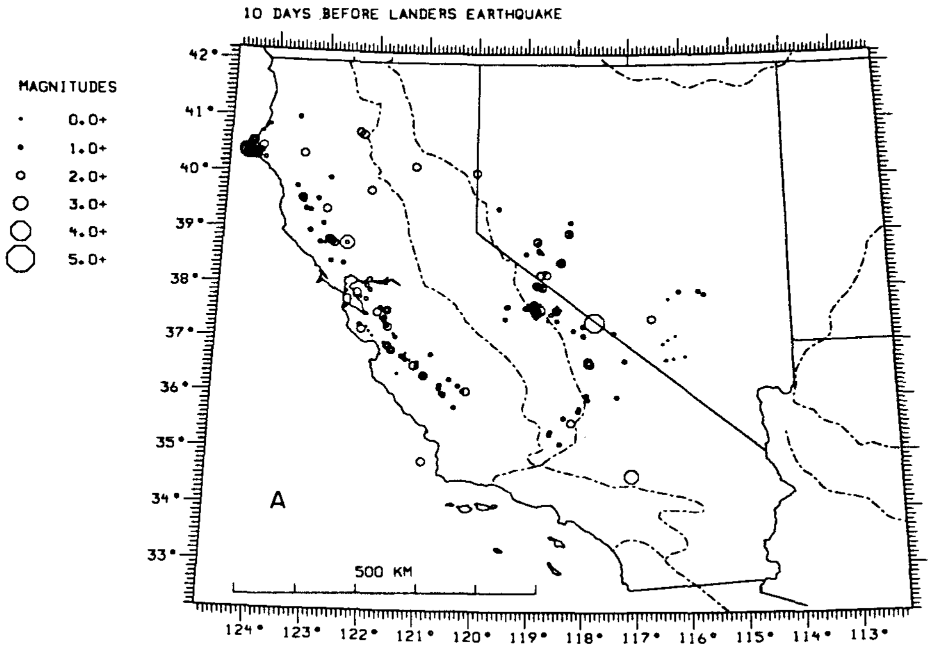
Within minutes after the Landers earthquake, local earthquake activity increased abruptly at widely scattered sites across the western United States (Figure 5; Reasenberg and others, 1992). This increase, while unusual, was not unprecedented. Some distant triggering may have been caused by the 1906 San Francisco earthquake -- notably a M6+ event in the Imperial Valley on the afternoon of the same day. Previous observations have shown that earthquakes can be induced or triggered by filling and emptying reservoirs, injecting and extracting fluids through deep boreholes, mining, detonating underground nuclear explosions, and other earthquakes. Aftershocks usually occur within one or two fault-lengths of the mainshock, however, with areas farther away generally remaining unaffected. Nevertheless, for the Landers event, triggered earthquakes appear to have occurred as far away as 17 fault lengths (1250 km).

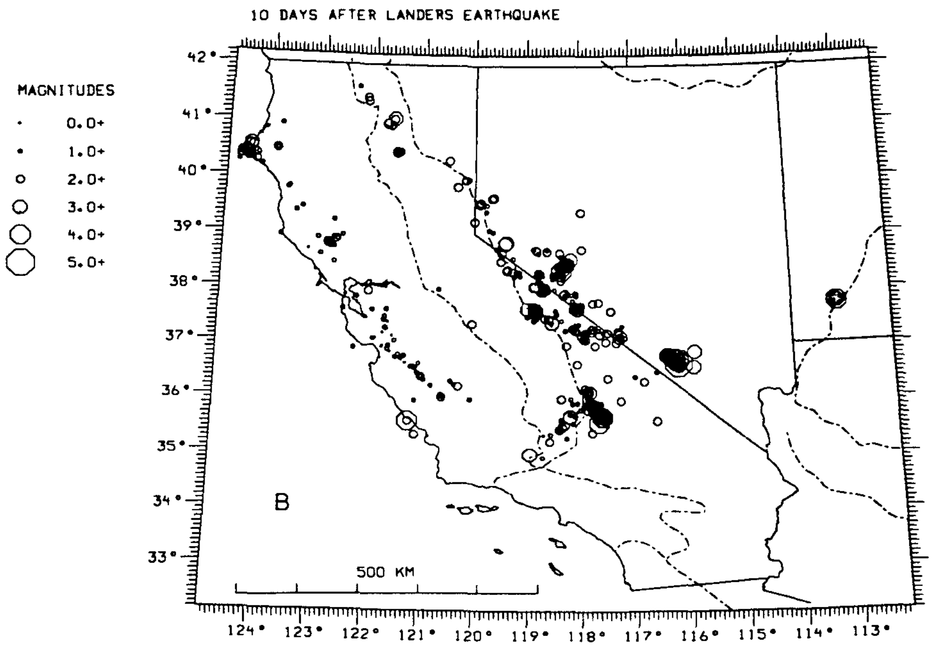
The clearest observations of probable triggered activity come from areas north and east of Landers (Figure 5). Indications of a widespread increase in earthquake activity in southern California also exist, but these remain equivocal because the regional earthquake catalog is incomplete -- an unavoidable consequence of backlogged processing due to the Landers aftershocks. In areas such as the Long Valley caldera and the Geysers, normally high seismicity rates became even higher in a sudden surge which started within 30 seconds after the local arrival of the seismic waves from the Landers quake and while the most energetic portion of the seismic waves from the Landers mainshock was still passing through these regions. In less active regions, such as Mono Basin, Mt. Shasta, and the White Mountains, the earliest candidates for triggered earthquakes are those detected between 8 and 24 hours after the mainshock. A dramatic increase in the earthquake rate occurred along the Sierra Nevada - Great Basin boundary from Owens Valley to Lake Tahoe. In the southern Cascade Range in California, seismic activity increased in areas near Mount Shasta, Medicine Lake Caldera, and Lassen Peak, but did not change further north in other volcanic centers of the Cascades.

In southern Nevada and eastern California, triggered events occurred in a broad zone extending northward from the Landers earthquake aftershock zone through Death Valley, east to Cedar City in southwestern Utah, and up to Yellowstone National Park. The biggest of these earthquakes was near Little Skull Mountain, Nevada, with a magnitude of 5.6, 22 hours after the Landers earthquake. The seismicity rate did not increase along the creeping section of the San Andreas fault or in the San Francisco Bay region. No rate changes were observed in northern Arizona, in the Rio Grande Rift zone in New Mexico, or along the Wasatch fault zone in Utah.

The causal relationship between the Landers earthquake and distant triggered earthquakes is unknown. However, the threat to public safety from similar long-distance triggering associated with future large earthquakes appears to be limited. The increased rate of events within two fault-lengths of the Landers mainshock might be explained by the static change in stress resulting from the Landers rupture. The occurrence of small events in more distant geothermal areas such as Mt. Shasta and Lassen Peak may be attributed to the dynamic stresses associated with seismic waves, which are much larger than the static stress change at those distances. Oddly, earlier large earthquakes near Cape Mendocino (i.e., the April 25, 1992 M7.2 Cape Mendocino earthquake and its large aftershocks) which were much closer to Mt. Shasta and Lassen Peak, did not trigger earthquakes in these same areas.

Figure 5. Top panel: Earthquakes listed in regional network catalogs for northern California, northern and southern Nevada, and Utah in the 10-day period before the June 28, 1992 Landers earthquake. All magnitudes are shown. Bottom panel: The same region for the 10-day period after the Landers earthquake.





A question raised by the public is whether two nuclear explosions at the Nevada Test Site (NTS) on June 19 and 23 might have triggered the Landers earthquake. Previous explosions at NTS have triggered earthquakes, but only very close by, even when the explosions have been much larger than the two in question, which were magnitude 3.0 and 3.9. As the earlier discussion makes clear, the Landers earthquake had a more effective source of triggers much closer -- namely the many aftershocks of the earlier Joshua Tree earthquake.

V. STATIC STRESS CHANGES CAUSED BY THE LANDERS EARTHQUAKE SEQUENCE

WGCEP 90 employed a quantitative method (after Dieterich, 1988) to include static stress changes to assess the effect of one event on the probability of a future event on a nearby segment. Including this effect for faults in the Bay Area slightly increased the estimated probabilities on most fault segments there and a similar calculation in southern California might increase the probability in that region.

Has the Landers earthquake changed the failure state of the San Andreas fault? One estimate of the proximity to failure on a fault is given by the Coulomb failure stress, which specifies that failure is promoted when there is an increase in the sum of the shear stress (acting on the fault plane) plus the friction-coefficient times the extensional stress (acting perpendicular to the fault plane). Stress changes by the Landers earthquake sequence have been modeled by Stein and others (1992), Harris and Simpson (1992), and Jaume and Sykes (1992).

Models indicate that moderate-sized earthquakes near Landers from 1975 to 1992 increased the proximity to failure along the impending Landers rupture. Stress changes resulting from the 1975 Galway Lake, 1979 Homestead Valley, 1986 North Palm Springs, and 1992 Joshua Tree earthquakes together caused an increase of about 1 bar (note: 1 bar equals 15 lbs/in^2 and corresponds to atmospheric pressure at sea level) in the proximity to failure at the future Landers hypocenter (Figure 6, Panel A). This is about 1-2 percent of the stress drop that occurred during the Landers earthquake. A similar stress transfer is consistent with the triggering of the Big Bear earthquake 3 hr and 6 min after the Landers shock. The Landers rupture increased by 1-3 bars the proximity to failure at the Big Bear hypocenter (Figure 6 -- Panel B, and Figure 8).

The Landers and Big Bear earthquakes also increased the static stresses on parts of the San Andreas fault (Figures 7 and 8). The largest estimated stress changes of 5-10 bars occurred along parts of the San Bernardino Mountains segment (Figure 8), which would have brought these parts closer to failure by an amount estimated to be equivalent to an advance of 10-20 years in the timing of the next large earthquake (Table 3). Smaller stress changes on the San Andreas fault to the southeast are estimated to have brought parts of the Coachella Valley segment closer to failure by an amount equivalent to 3 to 10 years. The Mojave segment to the northwest was slightly relaxed by the Landers-induced stress changes, by an amount equivalent to a delay of 0.3 to 10 years. The ranges in clock advances reported above are a consensus among Stein and others (1992) and Harris and Simpson (1992) and reflect differences in models and assumptions regarding fault geometry and averaging stress along the fault. Among other faults brought closer to failure in the models, parts of the San Bernardino Valley and San Jacinto Valley segments of the San Jacinto fault zone are estimated to have experienced a clock advance of about 5-8 years.

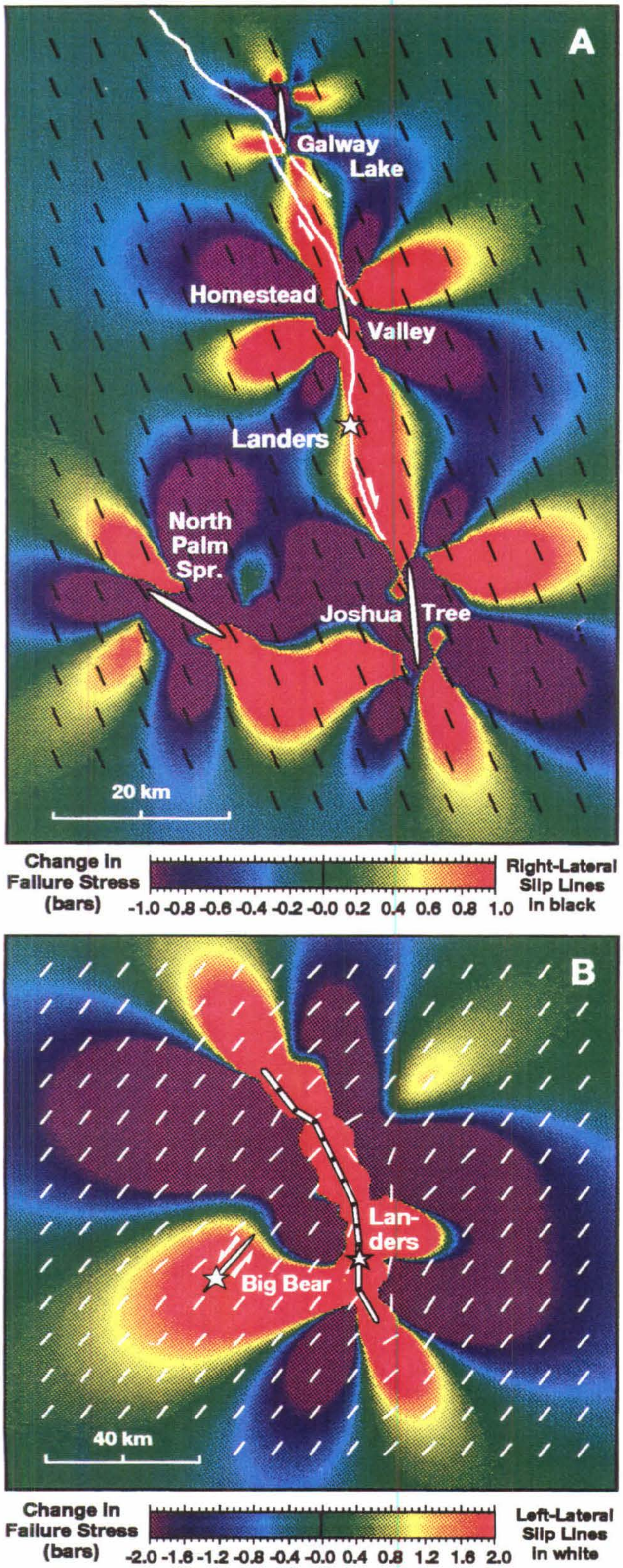


Figure 6.

Panel A: Optimum Coulomb failure stress changes (for a static friction coefficient, μ, of 0.4) caused by the four M≥5.2 shocks within 50 km of the Landers earthquake occurring during the previous 17 years. The optimum right-lateral fault planes are shown by the short black lines. Note the Landers epicenter and much of the fault rupture lies within the zone of elevated stress.

Panel B: Optimum Coulomb failure stress changes (for μ=0.4) caused by the Landers rupture. The optimum left-lateral fault planes are shown by the short white lines. The left-lateral Big Bear rupture, which followed the Landers shock by 3 hr 6 min, occurred in the largest region of stress increase of the Landers rupture. From Stein and others (1992).

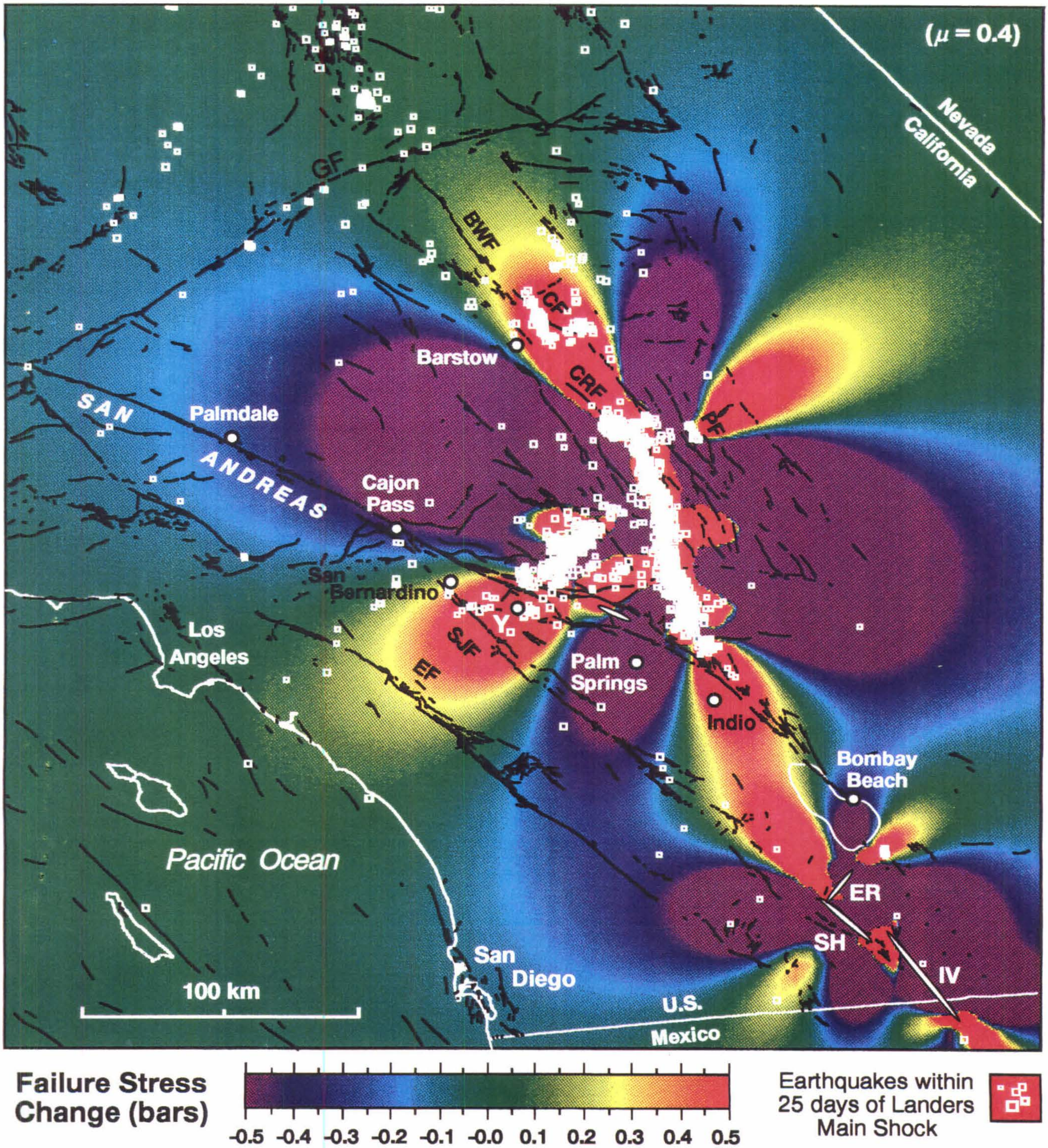


Figure 7. Optimum Coulomb failure stress changes caused by M≥6 earthquakes in southeastern California during 1979-1992. A regional compressive stress of 100 bars is oriented N7°E. Landers aftershocks are from Caltech-USGS network (M≥1). Stress changes caused by the Imperial Valley (IV), Elmore Ranch (ER) and Superstition Hills (SH) earthquakes are included. Stress has risen in the Coachella Valley (Bombay Beach to north of Indio) and the San Bernardino Mountains segments (north of Palm Springs to Cajon Pass). Stress has dropped on Mojave segment (Cajon Pass to west edge of map). Y = Yucaipa. Other faults are Elsinore (EF), San Jacinto (SJF), Garlock (GF), Camp Rock (CRF), Pisgah (PF), Lenwood (LF), and Blackwater (BF). From Stein and others (1992).

Figure 8. Changes in Coulomb failure stress for selected southern California faults and for fault planes of five M>4.5 aftershocks to the Landers earthquake. Red indicates that a fault was loaded toward failure in the model, and blue indicates relaxation. Landers rupture = yellow patches, SAFZ = San Andreas fault zone, M = Mojave segment, SB = San Bernardino Mountains segment, CV = Coachella Valley segment, SJFZ = San Jacinto fault zone, SBV = San Bernardino Valley segment, SJV = San Jacinto Valley segment, A = Anza segment, BM = Borrego Mountains segment, SMF = Superstition Mountains fault, SHF = Superstition Hills fault, IF = Imperial fault. M>4.5 aftershocks: bb = Big Bear Lake, br = Barstow, m = Mojave, p = Pisgah, rc = Ridgecrest. From Harris and Simpson (1992).

Panel A: Changes in Coulomb failure stress for a low apparent coefficient of friction, μ=0.2, which could represent either weak faults or the presence of pore fluids moderating the normal (perpendicular) stress changes.

Panel B: Changes in Coulomb failure for a high apparent coefficient of friction, μ= 0.8, which could represent either strong faults or, if pore fluids are present, the failure situation after enough time has passed for the fluids to re-equilibrate.

Note that four of the five M>4.5 aftershock fault planes were brought closer to failure by the Landers-induced Coulomb failure stresses.

A) $\mu = 0.2$

B) $\mu = 0.8$

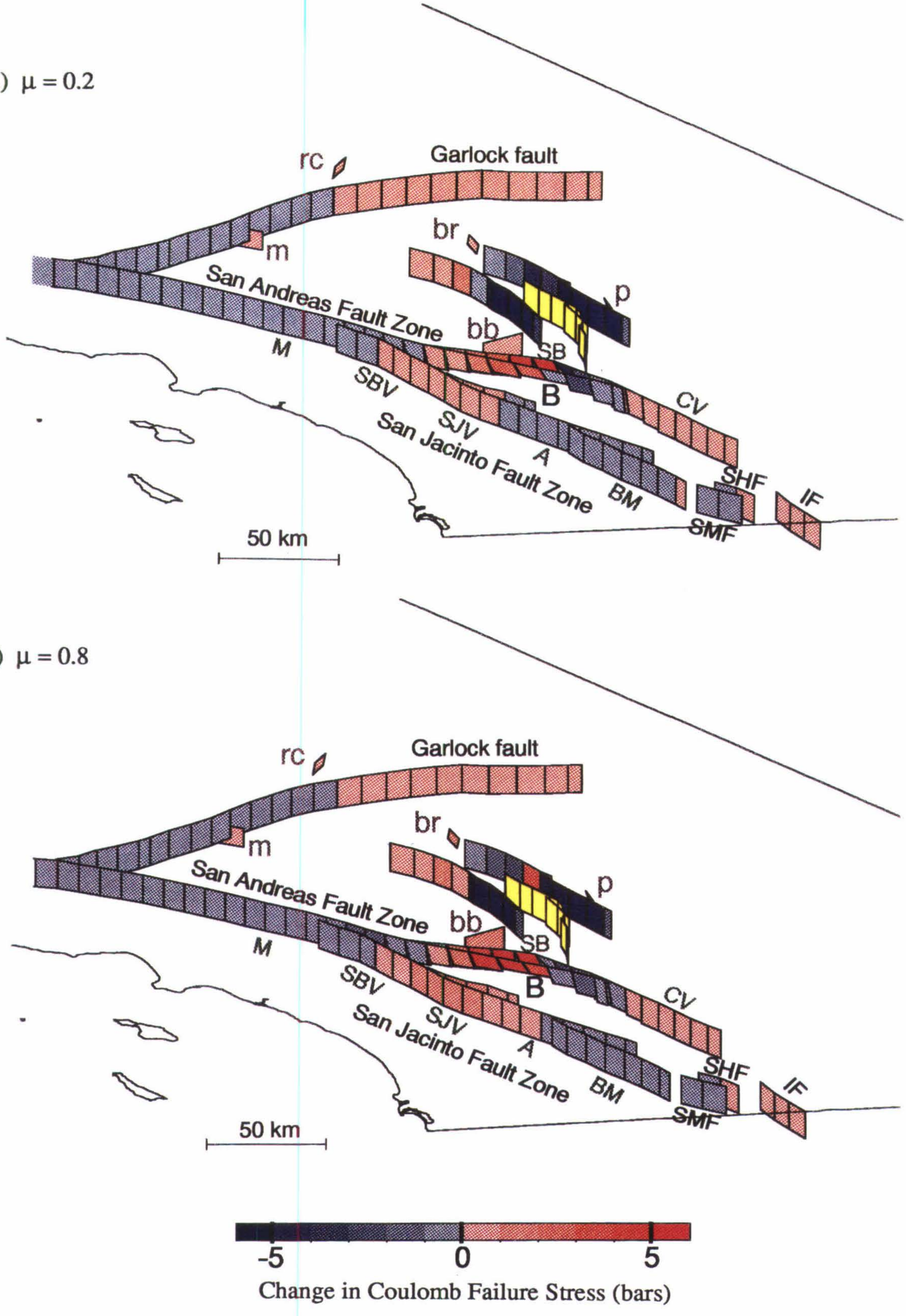


Figure 8

Table 3. Data Used to Estimate Clock-Advance Probabilities

Fault Segment	Last Event	Mean Recurrence Interval (yrs)	Standard Deviation *	Time Since Last Event (yrs)	Clock Advance (yrs) **
Mojave (SA)	1857	162	0.41	135	- 0.3 to -10 ***
San Bernardino Mountains (SA)	1812	198	0.60	180	10 to 20
Coachella Valley (SA)	1680	258	0.30	312	3 to 10
San Bernardino Valley (SJ)	1890	†	†	102	5 to 8
San Jacinto Valley (SJ)	1918	†	†	74	5 to 8

* The standard deviation of the natural logarithm of the ratio of the expected recurrence time to its mean.

** Derived using a plausible range of models, including the plate model of Stein and others (1992) and the halfspace model of Harris and Simpson (1992).

*** For this segment the clock was delayed 0.3 to 10 years.

† Data not available.

VI. PLAUSIBLE FUTURE LARGE EARTHQUAKES AS A CONSEQUENCE OF THE LANDERS EARTHQUAKE SEQUENCE

The WGCEP 88 report stated that there is a relatively high level of seismic hazard in southern California from the "ripeness" for rupture of the southern San Andreas fault. Since then, there have been new developments: (a) regional earthquake activity has increased since 1985 compared with the previous two decades, (b) the Landers earthquakes has occurred, and (c) the stress toward the failure limit has been increased on parts of the San Andreas fault. These factors may increase the chances of large earthquakes in southern California. However, the most probable outcome is for no M>7 earthquake in southern California during the next few years. In the last two centuries, the region has experienced about eight earthquakes greater than M7 (Table 4). If these large earthquakes are assumed to occur randomly in time, then this record implies a probability rate of about 4 percent per year.

In this section we consider the potential for a major earthquake ($M \geq 7$) occurring within approximately 100 km of the Landers rupture in the next few years (refer to Figure 1). If such an event were to occur, it would most likely nucleate on either a segment of the southern San Andreas fault, the northern San Jacinto fault, or a fault in the Mojave shear zone. Below we review the most plausible large earthquake scenarios on these structures given the occurrence of the Landers earthquake sequence.

Table 4. Big Earthquakes in Southern California

Year	Month	Day	M	Location
1812	12	8	7	Wrightwood
1812	12	21	7	Santa Barbara Channel
1857	1	9	8.2	Fort Tejon
1872	3	6	7.6	Owens Valley
1927	11	4	7.3	Southwest of Lompoc
1940	5	19	7.1	Imperial valley
1952	7	21	7.7	Kern County
1992	6	28	7.5	Landers

Data from Ellsworth (1990), and this report. Note that two large earthquakes, apparently separated by more than 100 km, occurred within two weeks in 1812.

Table 5. WGCEP 88 Fault Segments

Fault	Segment	Length (km)	Last Event	30-year Probability
San Andreas	Mojave	100	1857	0.3
San Andreas	San Bernardino Mountains	100	1812	0.2
San Andreas	Coachella Valley	100	1680	0.4
San Jacinto	San Bernardino Valley	50	1890(?)	0.2
San Jacinto	San Jacinto Valley	65	1918	0.1
San Jacinto	Anza	50	1892(?)	0.3

A. Southern San Andreas and Northern San Jacinto Faults

The southern 300 km of the San Andreas fault has been divided into three distinct segments, based upon the geometry of the fault, its historical seismicity, and the availability of paleoseismic data -- the Mojave, San Bernardino Mountains, and Coachella Valley segments. The northern San Jacinto fault has been divided into the San Bernardino Valley, San Jacinto Valley, and Anza segments (WGCEP 88; Figure 1 and Table 5). Paleoseismic data from several sites along the San Andreas (Table 6) indicate that large coseismic ruptures may commonly involve more than one segment. The multiple-segment character of the historical 1857 Fort Tejon and 1906 San Francisco ruptures support this conclusion. The possibility that recent prehistoric large earthquakes were produced by single segments acting alone, however, cannot be excluded by the paleoseismic data. Radiocarbon dating (the most commonly used method to date prehistoric earthquakes) cannot always distinguish two earthquakes occurring on two adjacent segments within a few decades of one another from a single event involving both segments, and vice versa. Thus, an earthquake at one site may be correlated with an earthquake at another site based upon indistinguishable radiocarbon ages, even though the events may be decades apart. Such a correlation would tend to overestimate probabilities of larger events.

(1) San Bernardino Mountains Segment: This segment is the most geometrically complex part of the southern San Andreas fault. The northwestern end of this segment was defined (WGCEP 88) as the southeastern limit of the 1857 rupture, northwest of Cajon Pass. It is also, in effect, the intersection of the San Jacinto fault with the San Andreas. The southeastern end of the segment was defined to be San Gorgonio Pass. By this definition, the San Bernardino

Table 6. Earthquake Surface Rupture

	Coachella Valley	San Bernardino Mountains		Mojave		Carrizo	
Earthquake	Indio	Pitman Canyon	Cajon Creek	Wrightwood	Pallett Creek	Mill Potrero	Carrizo
1857				X	X	X	X
1812		X	X	X	X		
1690	X	X	?	X			
1590		?	?	X	?		
1490	X	?	?	X	X	X	X

Recent trenching studies at Wrightwood, Pitman Canyon (near Devore) and Indio, combined with the previous work by Sieh (1978) at Pallett Creek, give more precise dates and sizes of earthquakes on the San Andreas fault than were available in 1988. No information exists at Pitman Canyon for 1690. Cajon Creek suffered two additional events between 1290 and 1812; but dates are unknown. 1690 is a revised estimate of the date of the "1680" event referred to by WGCEP. The 1680 date is used in Tables 3 and 5 for conformity with WGCEP 88.

Mountains segment includes most of the San Andreas fault between the southern tail of the Landers/Joshua Tree earthquake sequence and the southwestern tail of the Big Bear aftershock zone (Figure 2a). Results discussed earlier indicate that the Landers and Big Bear ruptures decreased the normal stress and increased the right-lateral shear stress on this portion of the San Bernardino Mountains segment between the two aftershock zones. Furthermore, a small patch of the San Bernardino Mountains segment slipped in the North Palm Springs earthquake of 1986 (Jones and others, 1986), indicating that this segment may be ready for a larger rupture.

Its relatively long period of dormancy may also indicate that the San Bernardino Mountains segment may be near failure. Sites at Wrightwood, just a few km northwest of the segment and at Pitman Canyon within the segment, show evidence of ruptures in 1690 and 1812. If the 1690 event is the same one detected at Indio, then it must have ruptured the entire San Bernardino Mountains segment. Likewise, we might assume the event in 1490 ruptured through the segment because of surface rupture at both Indio and Wrightwood. If the 1812 earthquake ruptured the San Bernardino Mountains segment, then the mean recurrence time since 1490 is about 167 years (502 divided by 3), and an elapsed time since rupture is 180 years. If, on the other hand, the 1812 event did not continue southeast of Wrightwood/Pitman Canyon, then the mean recurrence time is 251 years (502 divided by 2), and the elapsed time is about 300 years. In both cases the elapsed time exceeds the mean recurrence time.

Two facts suggest, however, that the San Bernardino Mountains segment may not be in imminent danger of failure: (a) The North Palm Springs earthquake did not trigger a larger earthquake, and (b) very few aftershocks (potential triggers) of the Joshua Tree, Landers, or Big Bear earthquakes have occurred on the San Andreas fault. The aftershocks near Yucaipa are a concern, especially those with focal mechanisms expected for San Andreas fault earthquakes, and these continuing aftershocks and the strain field accompanying them merit careful monitoring. Should additional moderate sized earthquakes occur on the San Bernardino Mountains segment, the likelihood for future rupture of this segment would increase.

Immediately following the April 22, 1992, Joshua Tree event (M6.1), the USGS office in Pasadena applied the model of Agnew and Jones (1991) to determine the probability that an earthquake of a given magnitude on the San Andreas fault is a foreshock to a larger earthquake. The OES was notified that there was a 5 to 25 percent chance of a large earthquake on the San Andreas fault within the 72 hours immediately following the Joshua Tree event, and OES issued a public advisory. However, because Agnew and Jones (1991) did not consider the possibility of a large earthquake sequence (such as Landers/Big Bear) that had numerous aftershocks in the vicinity of the San Andreas fault, it may be inappropriate to use their model to estimate the probability that Landers/Big Bear aftershocks will be foreshocks to a larger San Andreas event. At this point, the hazard ensuing from the occurrence of such an earthquake cannot be quantified, but as is the case with most potential aftershocks, the chance that a large San Andreas earthquake would follow a M6 is probably small. Still, the consequences of such an event are serious and it would appear to be appropriate that OES take precautionary measures including planning for an alert and mobilization in response to a M6 or larger event occurring on or near the San Andreas fault between Cajon Pass and Bombay Beach.

If the San Bernardino Mountains segment should fail in the next few years, its complex fault geometry suggests that the coseismic deformation will also be complex; the event would probably be well over M7. Assuming a 25 mm/yr long-term slip rate (Weldon and Sieh, 1985), between 4.5 and 7.5 m of right-lateral displacement would occur along the principal rupture, with the potential for a lesser, but not insignificant, component of reverse slip. The large number of active secondary structures and numerous changes in strike and dip along the segment suggest that aftershock activity could be unusually robust and complex.

(2) Coachella Valley Segment: The Coachella Valley segment is the most likely segment of the San Andreas fault to fail in the next 30 years (WGCEP 88). This conclusion was based on paleoseismic data near Indio which indicate that between about 1000AD and 1700AD the average time interval between large earthquakes was about 230 years, but that the most recent seismic rupture occurred about 300 years ago. As noted earlier, calculations indicate that the Landers and Big Bear ruptures slightly increased the right-lateral shear stress on this fault segment. If this segment fails soon, right-lateral offsets of about 9 meters could be expected given the current period of dormancy and long-term slip rate of about 30 mm/yr.

(3) Mojave Segment: This segment was not strongly perturbed by the Landers and Big Bear earthquakes or their aftershocks, and the stress may have moved farther from the failure limit by a small amount. Nevertheless, this segment is relatively hazardous (WGCEP 88), and the Landers event has not changed this conclusion.

(4) Combinations of San Andreas Segments: Since 1988 new paleoseismic data have become available (e.g., Table 6), and our understanding of seismicity along the southern San Andreas fault system has advanced. The paleoseismic data show that either earthquakes frequently rupture across segment boundaries or that adjacent segments tend to rupture within a short time of one another (Sieh and others, 1989). Simultaneous rupture of the San Bernardino Mountains and Coachella Valley segments is certainly plausible, and this scenario would entail rupture of the southern 200 km of the San Andreas fault in an earthquake of about M7.8.

Part of the 100-km-long Mojave segment moved with the San Bernardino Mountains segment in 1812 and could do so again. If the Mojave segment failed in conjunction with the San Bernardino Mountains and Coachella Valley segments, the rupture length would be about 300 km, and the earthquake would be about M8. The probability for such a multisegment event is lower than that for the individual segments.

(5) Northern San Jacinto fault: Although the southern half of the San Jacinto zone has produced numerous moderate earthquakes throughout the past half century, the northern half has been seismically quiet since the occurrence of major earthquakes in 1899 and 1918. Earthquakes greater than M7 are plausible on the Anza, San Jacinto Valley and San Bernardino Valley segments (WGCEP 88). The Landers sequence caused the stress to move closer to the failure limit on the San Bernardino Valley and San Jacinto Valley segments of the San Jacinto fault, although to an even smaller extent than it did on the sub-parallel San Andreas.

B. Miscellaneous Faults of the Mojave Shear Zone

The Landers earthquake was generated by the sudden failure of interconnected fault segments on several different faults within the south-central part of the Mojave shear zone. Many more fault segments within this 90-km-wide zone of active right-lateral faults did not fail during the earthquake, but, because of their proximity to the rupture, fall within the region of appreciable coseismic static stress change. As discussed earlier, modeling of the stress change indicates that some of these structures experienced effects that would inhibit failure, while others underwent changes that might accelerate failure. Furthermore, the Landers and other earthquakes in southern California over the last 7 1/2 years may indicate increased stress over a broad region. This stress might be large enough to push some unrecognized fault toward the failure point.

The recurrence of major ruptures along each active fault in the Mojave shear zone is probably measured in millennia, rather than centuries. If this is correct, the annual probability of rupture of any one fault would be much lower than for faults of the San Andreas system where recurrence intervals are typically shorter by an order of magnitude. Furthermore, several of this century's M>7 earthquakes, including the 1954 Dixie Valley-Fairview Peak, 1932 Cedar Mountain, 1915 Pleasant Valley, and 1872 Owens Valley earthquakes, effectively occurred on a northward extension of the Mojave shear zone and have originated on faults with similarly long recurrence intervals. The dates of the most recent large earthquakes on faults of the Mojave shear zone are unknown, however, and one or more could be similar to the Landers rupture -- i.e., "ripe" for failure. The larger ones could generate M7 earthquakes if they were to fail, making any of these faults, singularly or in conjunction with its neighbors, a possible source for the next major earthquake in southern California.

Of particular concern is the Calico-Blackwater fault zone. Since the Landers event, a well-defined zone of aftershocks has been developing just southwest of this fault zone -- to the northeast of Barstow (Figure 2a). The spatial relationship of these quakes to the Calico-Blackwater faults resembles that of the Homestead Valley earthquakes in 1979 to the Homestead Valley /Johnson Valley faults on which the Landers rupture occurred. Another area of concern is a gap in aftershocks between the northern termination of the Landers rupture on the Camp Rock fault and a zone of aftershocks northeast of Barstow (Figure 2a). This roughly 40 km gap could be filled with a M6+ aftershock, thus affecting the Barstow area.

VII. INTERMEDIATE-TERM (1 TO 5 YEAR) PROBABILITY ESTIMATES

In the last section we examined the likelihood of failure of the faults within 100 km of the Landers rupture. In this section we quantitatively assess the probability of earthquake occurrences in the intermediate term for regions potentially impacted by the Landers earthquake as well as for greater southern California. We first consider the immediate impact of the Landers earthquake sequence on the San Andreas and San Jacinto faults, and then examine probabilities for the greater Landers and southern California regions without regard to specific faults. For the latter we rely mainly on earthquake catalogs. Because few historical precedents exist and those that do are for rather different circumstances, probability cannot easily be addressed as frequency of occurrence or as a description of well-categorized randomness. Rather, probability must be interpreted as betting odds. We consider a number of techniques below, covering a spectrum from very empirical to very model dependent. Generally the empirical techniques are based on global earthquake observations which are numerous but fail to capture the special circumstances of the present case. The model-dependent techniques are based on assumptions that are reasonable but untestable because of insufficient data.

The probability estimates below are for periods beginning September 1, 1992. Most are driven by the fact that no large earthquake has occurred between the time of the June 28, 1992, Landers earthquake and September 1, 1992, and we have explicitly included this fact.

A. Southern San Andreas and Northern San Jacinto Faults

The WGCEP 88 report calculated the probability of a large event on a specific segment of the San Andreas fault given the time elapsed since the last such event, but did not address the effects of one fault or segment of fault upon another. The report assumed that earthquakes on a given segment are quasi-periodic, with a probability density function for inter-event times given by the log normal distribution.

Since the Landers earthquake did not occur either on the San Andreas or San Jacinto fault, we assume that it did not reset the clock to zero for any of the San Andreas or San Jacinto segments. However, one way to approach a revision in probabilities (WGCEP 90) for these faults is to add the time it would take to accumulate aseismically the change in Coulomb failure stress on the San Andreas or San Jacinto fault caused by the Landers earthquake to the elapsed time since the last earthquake ("clock advance"). We estimated one-year probabilities for segments of the southern San Andreas and the northern San Jacinto from the data in Table 3. They were not perceptibly different from those calculated using the same methods as WGCEP 88, without the clock advance. The negligible change in probability predicted by the clock advance method may not adequately reflect the change in seismic hazard. It is based on a simple quasi-periodic model for earthquake occurrence that may not capture the true physics of stress interactions following a large earthquake. The sequence of quakes beginning with the 1975 Galway Lake earthquake and culminating with the Landers event suggests that the stress increment form each earthquake helped trigger the next one. Another remarkable sequence of earthquakes occurred along the North Anatolian fault in Turkey from 1939 to 1944. However, examination of global earthquake catalogs shows that such apparent triggering is far from universal. When considering failure criteria, the irregular geometry and heterogeneous distribution of strength along a fault may be more important than stress increments from nearby earthquakes. Since more time is needed to discuss these issues, we will defer a more complete analysis of the probability estimates for individual segments of the San Andreas and San Jacinto faults to the Phase II report.

B. Greater Landers Region

Let us now estimate the probability of a large earthquake (M>7) occurrence in the greater Landers region without regard to specific faults. For convenience, this region will be described by a rectangular box with latitude range 33.5^{0} N to 35.5^{0}N and the longitude range 115.5^{0}W to 117.5^{0}W (Figure 1). Using data for the southern California catalog from 1932 through 1991 (truncated at M5) and the catalog of historic M>6 earthquakes compiled by Toppozada and others (1986; updated to include events through July, 1992; Table 4), we first estimate the probability assuming that earthquakes occur with a yearly probability independent of the time of the last earthquake (the Poisson model). Within the zone we should expect M>5 earthquakes at the rate of 1 per year, M>6 at 0.1 per year, and M>7 at 0.01 per year. These figures assume that the rate of occurrence has not changed in the last few years and ignore the special circumstances of the present situation. We use these estimates as a benchmark and refer to the "probability gain" as the ratio of the conditional probability estimated by an alternative model to that estimated by this Poisson model.

One of the special circumstances (the recent occurrence of a large earthquake) can be accounted for by examining earthquake catalogs for similar occurrences. Most large earthquakes cause a sizable stress redistribution similar to Landers, so this method may account partly for this effect as well. A global catalog of M>7 earthquakes since 1900 (Pacheco and Sykes, 1992), was searched for pairs of events within 100 km and five years. Of the 697 events in the catalog, 69 were followed by subsequent large earthquakes within 60 days, and 16 others were followed by subsequent large events from 2 to 14 months later. A rough probability estimate for the one year period beginning September 1, 1992, comes from the ratio 16/697 = 0.0230 (Table 7). Excluding the first two-month interval to account for the absence of a large earthquake before September 1, 1992, strongly affects the conditional probability. The two month remission is a good sign.

The earthquakes and earthquake pairs in the catalog are dominated by subduction zone events which may behave differently from strike-slip earthquakes. Of the pairs within 2 months, only 3 of 69 began with a strike slip earthquake, and of the 16 pairs within 2 to 14 months, none began with a strike slip event. However, the data are insufficient to infer a difference between strike-slip and other events.

The Harvard catalog (Dziewonski and others, 1992), which covers the period from 1977 through July, 1992, provided 154 large earthquakes, 16 of which were followed by subsequent large earthquakes within 2 months, and 5 were followed in the period 2 to 14 months. The ratio 5/154 = 0.0325 is consistent with the one-year probability estimated above from the Pacheco and Sykes catalog.

Table 7. Conditional Probability Estimates for Landers Area (M≥7)

Method	1 year	5 year	Reference
Poisson (a=5.0, b=1.0)	0.01	0.049	Jackson and others, 1992
Global Pairs	0.023		Pacheco and Sykes, 1992
Global Pairs, Harvard Catalog	0.032	0.12	Kagan and Jackson, 1991
Aftershocks	0.046	0.13	Reasenberg and Jones, 1989
Clustering p=0.5	0.014	0.045	Kagan and Jackson, 1991

Statistics derived from the global catalog may not apply directly to regional issues in southern California. An alternate approach uses a scaling relationship to model the functional form of regional or global seismicity, and then adjusts parameters to fit the local rate, magnitude distribution, and recent history (e.g., Reasenberg and Jones, 1989). The model predicts a sudden jump in aftershock rate followed by a decay with time after the triggering event. The triggering potential of a given earthquake increases exponentially with the magnitude of the earthquake. These parameters were chosen to fit a large collection of aftershock sequences in California and can be adjusted to fit the characteristics of a specific aftershock sequence, but the generic parameters described the Landers aftershocks well. The model predicts an extra probability of 3.6 percent and 8 percent for one-year and five-year periods beginning September 1, 1992, respectively. Assuming that the Poisson rate (Table 7) estimated above is based on independent (as opposed to triggered) earthquakes, then the rate of triggered events can be added to the rate of independent events (probabilities of 4.6 percent for 1 year and 13 percent for five years as shown for "Aftershocks" in Table 7).

Kagan and Jackson (1991) studied the correlations in space and time for earthquakes in several global and regional catalogs. They derived a model similar to the Reasenberg and Jones (1989) model, with a few important differences, and found that triggered seismicity decreases inversely with distance from the triggering event. They also summed the triggering potential for all previous earthquakes, whereas Reasenberg and Jones treated the ensuing seismicity as triggered by a single designated mainshock. Parameters for the Kagan and Jackson model were fit to the Harvard catalog of global earthquakes with M>5.5; the model predicts only a small increase over the Poisson rate.

C. Greater Southern California

For the entire southern California region, Jones (1992b) found that the seismicity for M>5 has increased substantially since 1985 (Table 1). The rate of occurrence of moderate earthquakes can be extrapolated to estimate the rate for larger events; the inferred rates for M7 and larger earthquakes are 0.017 per year for 1945-1984, and 0.127 per year since 1985. We do not know if this increased activity will persist in the future and be a departure from the lower average background rate of 0.04 events per year based on historic earthquakes (Table 4). But if it does, the probability of a M>7 earthquake in greater southern California in the next year will be three times higher than that based on the long term rate, or 12 percent assuming the Poisson model (Table 8).

The above probability based on the recent short-term rate is considered to be an over-estimate by some scientists. For example, a statistical analysis of southern California seismicity as a cluster model with memory described by Kagan and Jackson (1992) gives a more conservative estimate of the probability -- namely 5.5 percent for a M>7 earthquake in the next year (Table 8).

Table 8. Probability Estimates for Southern California (M≥7)

Model	1-year	5-year	Reference
Poisson, 1945-1984	0.017	0.081	Jones, 1992
Poisson, 1985-1992	0.12	0.47	Jones, 1992
Poisson, 1800-1992	0.04	0.18	Jackson, 1992
Cluster with memory	0.055		Kagan and Jackson, 1992

VIII. ESTIMATES OF GROUND SHAKING INTENSITY FOR FUTURE EARTHQUAKES

A comparison of the estimated ground shaking potential for the anticipated large earthquakes discussed above with the shaking experienced during the Landers earthquake shows strong, potentially damaging shaking over a wide area (Figure 9). We calculated the Modified Mercalli Intensity (MMI) using methods of Evernden and others (1981). The estimated intensities range from MMI V to IX which correspond to descriptions of ground shaking summarized in Table 9.

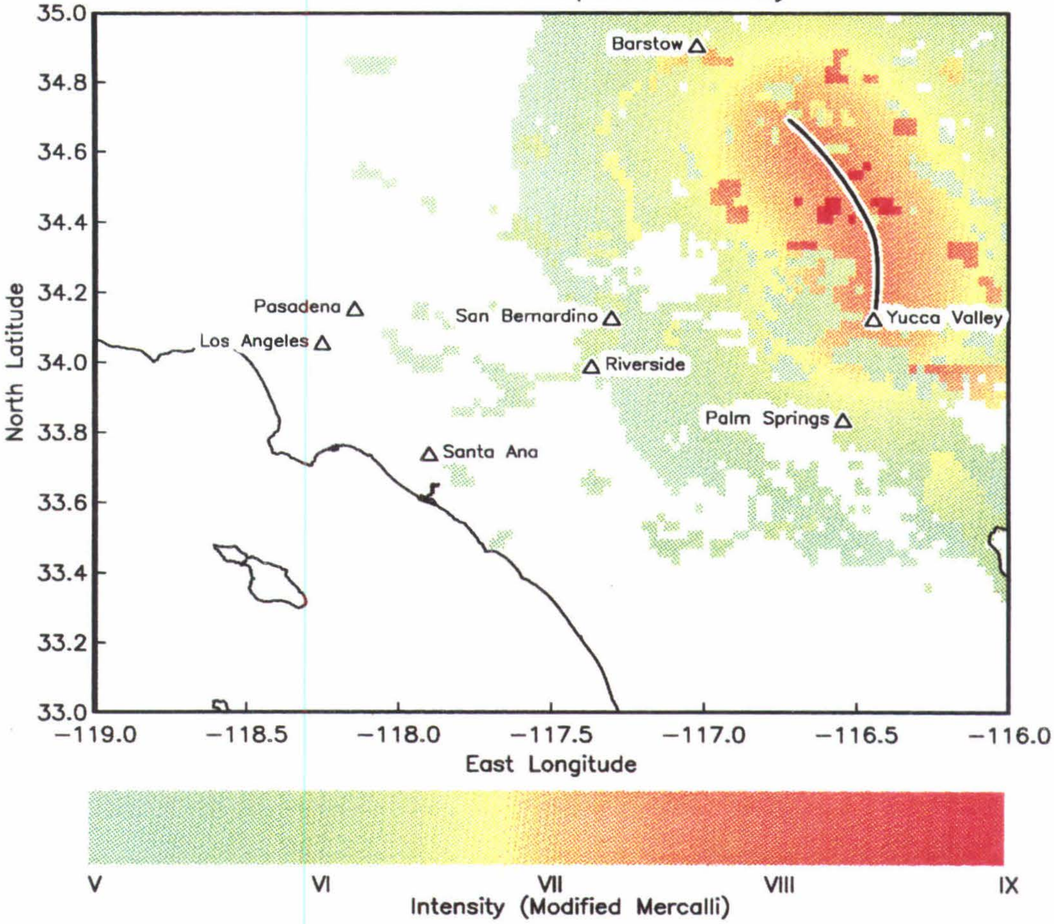
A comparison (Table 10) of the intensities observed at several locations with those predicted by Evernden's method (assuming a ground correction factor of -0.5 intensity units, corresponding to alluvium with a lowered groundwater table) compare reasonably well, although the program appears to underpredict the intensities in the Los Angeles area. The predicted intensities for the Landers/Yucca Valley area is MMI VII to VIII, in keeping with the actual levels of damage. The high intensity in the epicentral area is also consistent with an acceleration of 0.88g recorded at Lucerne Valley by an accelerograph operated by Southern California Edison Company (T.A. Kelly, written communication, 1992).

Comparison of the maps of intensities for anticipated large earthquakes with that for Landers indicates that earthquakes in the Mojave shear zone will have minor effects on urban areas of southern California. On the other hand, ruptures on the San Andreas and San Jacinto faults would cause strong shaking in some of the inland urban areas (Figures 9C to 9F. The intensity at a specific site in Figures 9A to 9G may be translated into a description of shaking (Table 9). For example, at Palm Springs the predicted intensity for Landers is MMI VI 1/2, but for a San Andreas event on the San Bernardino Mountains segment the estimated intensity at Palm Springs approaches MMI VIII.

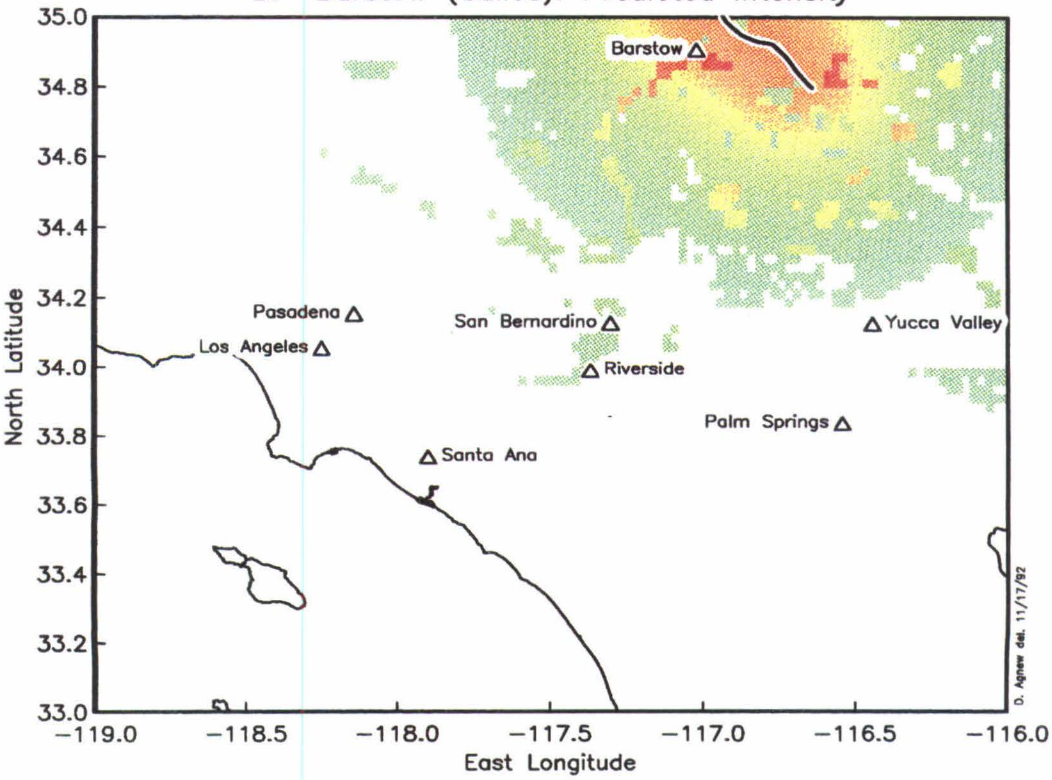
Figure 9. Predicted intensity for the Landers earthquake, and possible future events. Panels A to G are the intensity maps for the major urban areas of southern California due to the Landers earthquake and some plausible large earthquakes considered in Section VI. The maps show the Modified Mercalli intensities computed using the procedures of Evernden and others (1981). The mapped range of intensities is from V to IX. These intensities correspond to the descriptions of ground shaking given in Table 9.

Panel A:	Landers
Panel B:	Barstow (Calico)
Panel C:	San Andreas (San Bernardino Mountains)
Panel D:	San Andreas (Coachella Valley)
Panel E:	San Andreas (San Bernardino Mountains and Coachella Valley)
Panel F:	San Andreas (San Bernardino Mountains and Mojave)
Panel G:	San Jacinto (North)

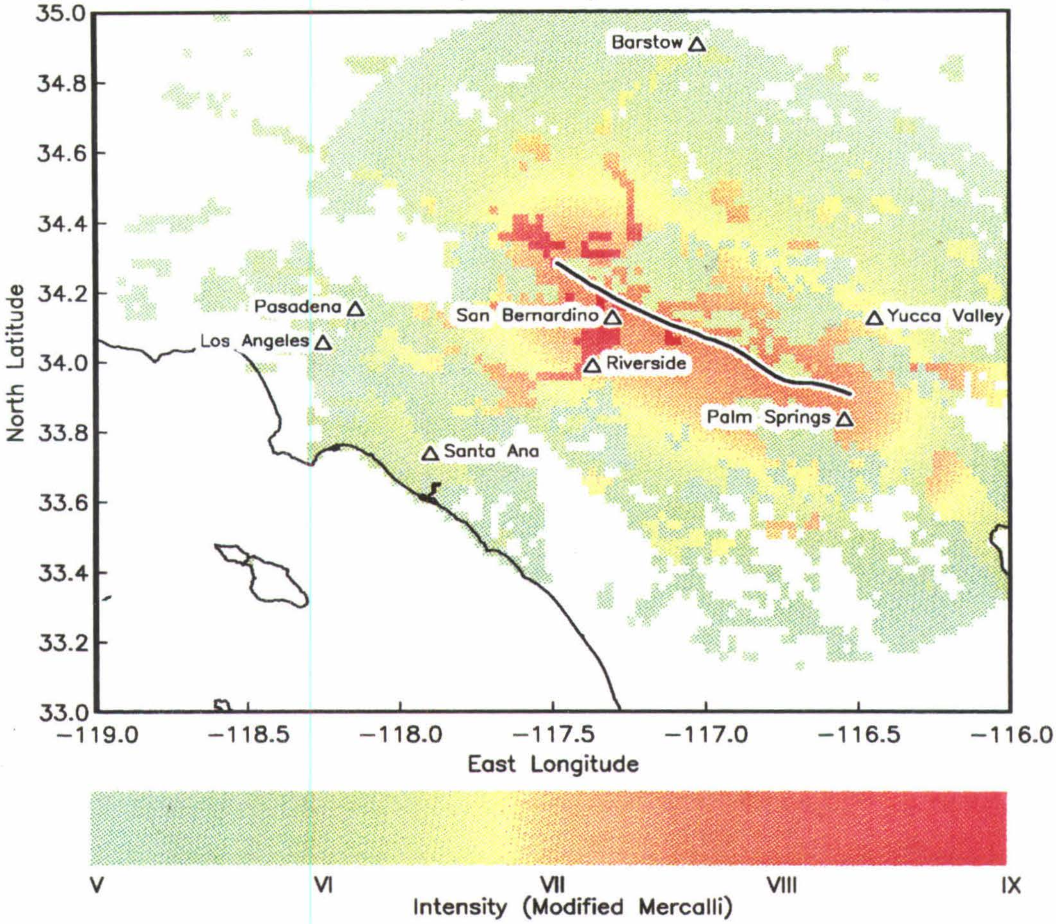
A. Landers: Computed Intensity



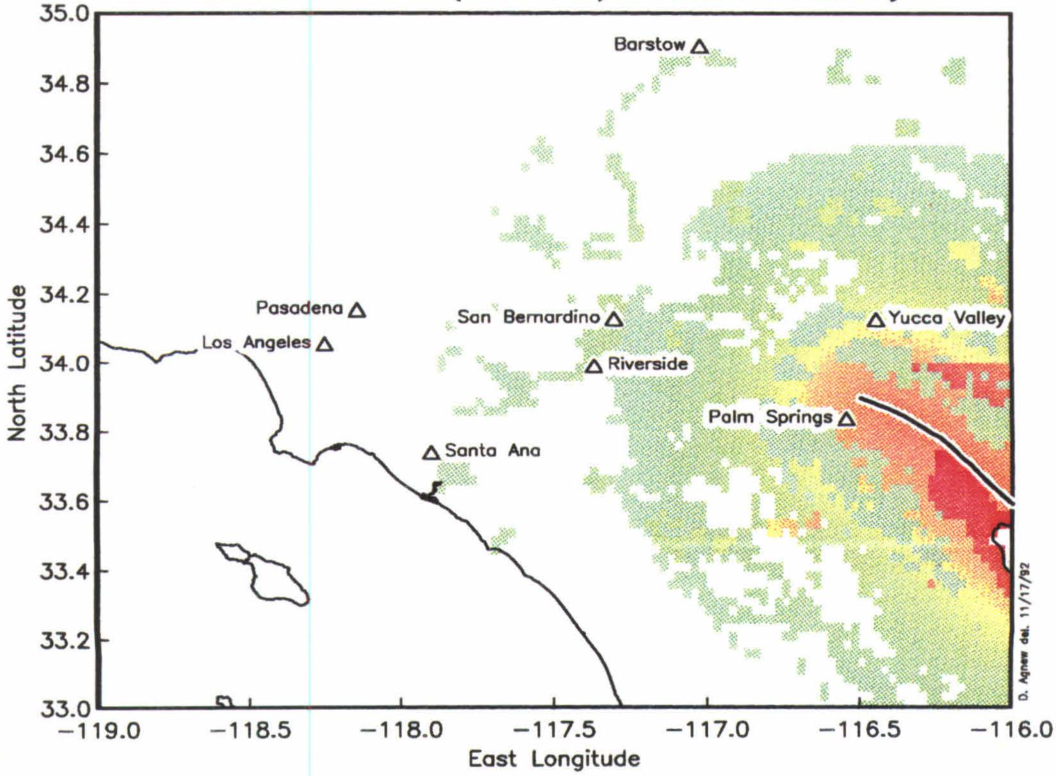
B. Barstow (Calico): Predicted Intensity



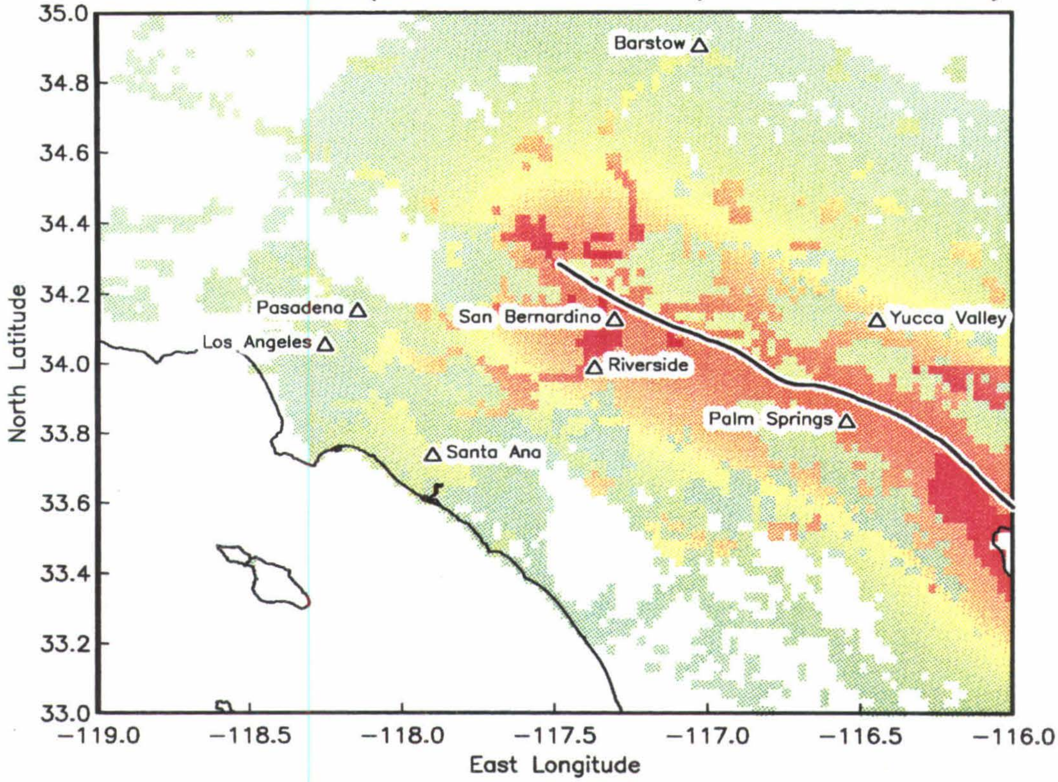
C. San Andreas (S.B Mtn.): Predicted Intensity

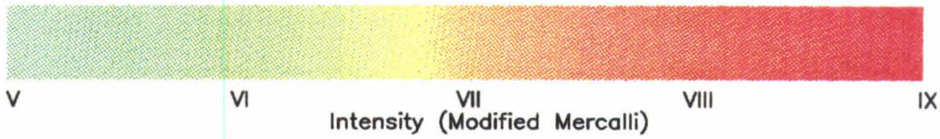


D. San Andreas (Coachella): Predicted Intensity

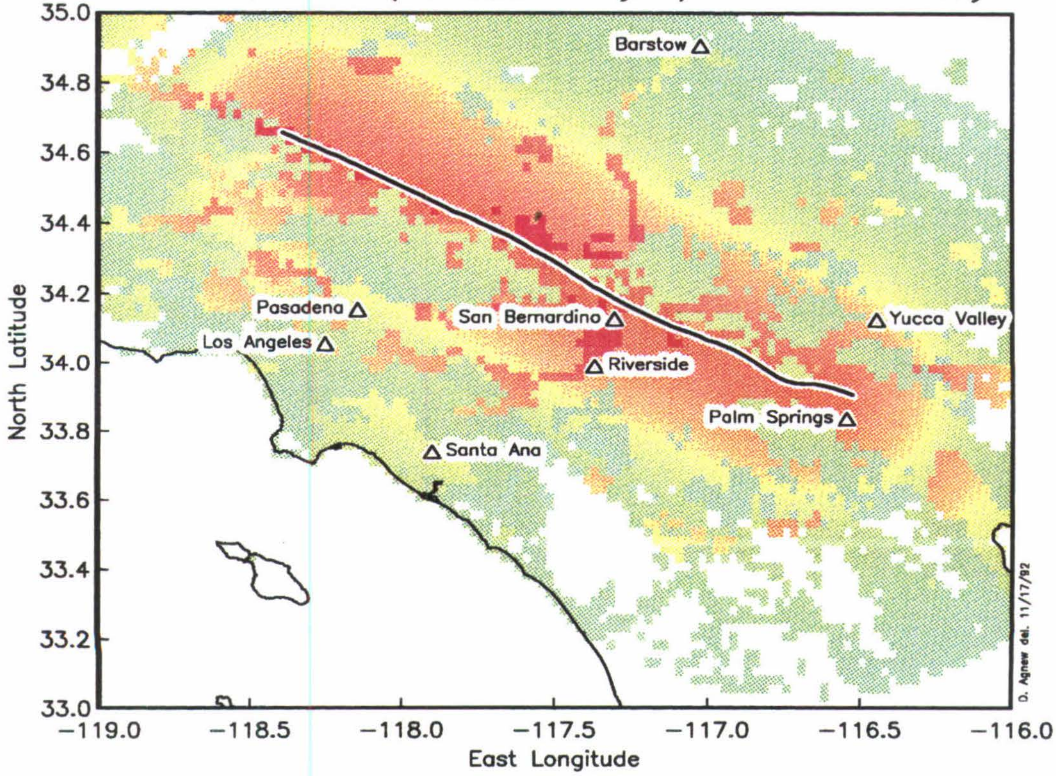


E. San Andreas (S.B Mtn. + Coachella): Predicted Intensity





F. San Andreas (S.B Mtn. + Mojave): Predicted Intensity



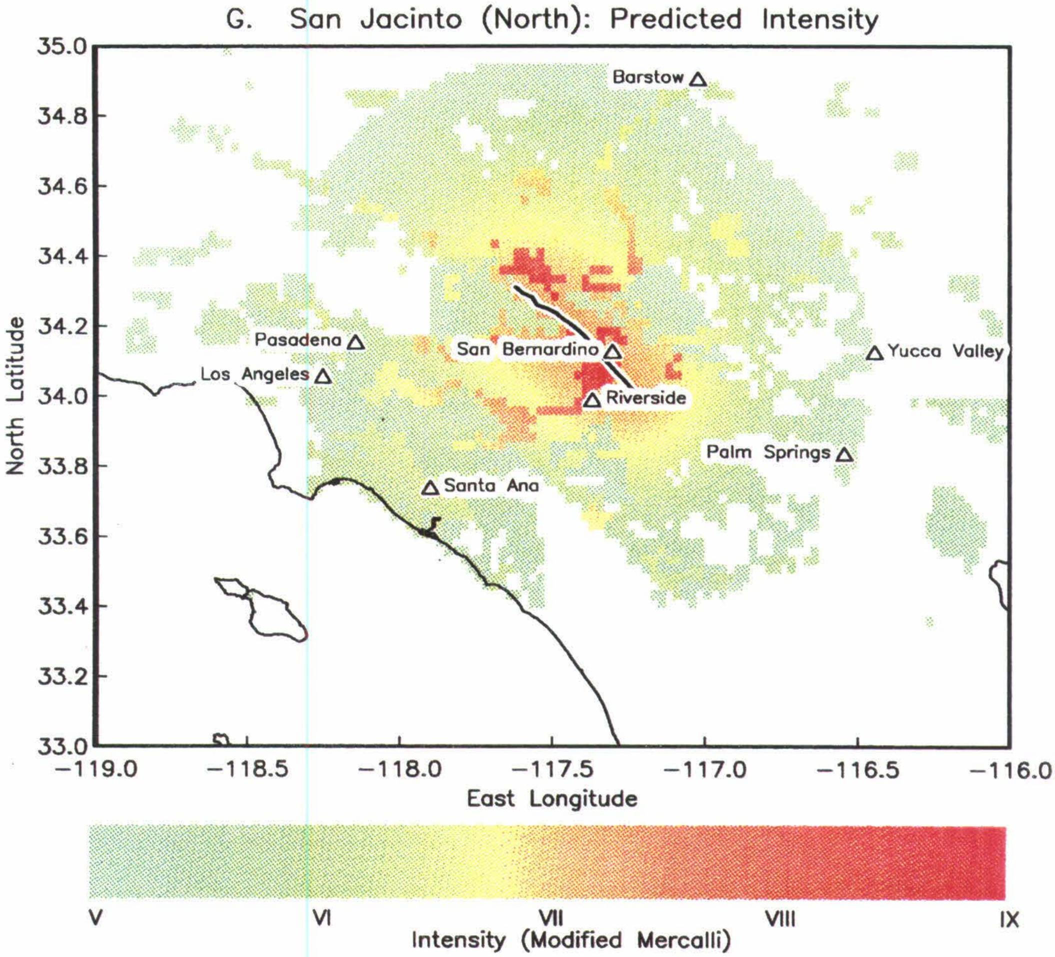

G. San Jacinto (North): Predicted Intensity
35.0
34.8
34.6
34.4
34.2
34.0
33.8
33.6
33.4
33.2
33.0
North Latitude
−119.0
−118.5
−118.0
−117.5
−117.0
−116.5
−116.0
East Longitude
Barstow
Pasadena
Los Angeles
San Bernardino
Yucca Valley
Riverside
Palm Springs
Santa Ana
V
VI
VII
VIII
IX
Intensity (Modified Mercalli)

Table 9. Modified Mercalli Intensity Scale of 1931 (Steinbrugge, 1982)

IV. During the day felt by many, felt outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls make creaking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.

V. Felt by nearly everyone; many awakened. Some dishes, windows, etc. broken; a few instances of cracked plaster; unstable objects overturned. Disturbance of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop.

VI. Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight.

VII. Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motor cars.

VIII. Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimney, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Disturbs persons driving motor cars.

IX. Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb; damage great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.

Table 10. Observed and Predicted Landers Intensities

Place	Observed	Predicted
Barstow	VI-VII	VI 1/2
Cherry Valley	VI	VI
Forest Falls	VII	VI 1/2
Joshua Tree	VII-VIII	VIII
Los Angeles	VI	IV 1/2
Morongo Valley	VII	VII 1/2
Palm Springs	VI+	VI 1/2
Pasadena	V-VI	IV 1/2
Redlands	VII	VI
Yucca Valley	VIII	VIII

IX. CONCLUSIONS

The Landers earthquake occurred on a series of interconnected fault segments within the Mojave shear zone, which accommodates 15-20 percent of the total displacement across the North American-Pacific plate boundary. The surface faulting from the Landers earthquake was almost entirely within one of the Special Studies zones designating active faults, although the actual combination of faults along the zone of rupture was not anticipated.

One reason for public concern over the Landers earthquake is the perception that there have been many earthquakes lately. This perception is accurate for southern California. Since 1985, M5 and larger earthquakes have occurred at a rate 1.7 times higher than for the previous four decades. For M6 and above, the rate is up by a factor of 3.6. We do not know if this change represents a short-term fluctuation or a persistent trend.

The Landers event belongs to an earthquake sequence which includes the 1975 Galway Lake (M5.2), 1979 Homestead Valley (M5.6), 1986 North Palm Springs (M6.0) and 1992 Joshua Tree (M6.1) quakes. The stress redistribution from these events is estimated to have increased the stress toward the failure limit along most of the future Landers rupture by about 1 bar. The Joshua Tree earthquake occurred April 22, 1992, on the same general fault zone as the Landers rupture, and in early June its aftershocks began to spread northward toward the future epicenter of the Landers mainshock. In retrospect, we consider a few of these events to be Landers foreshocks occurring at the site of the future Landers epicenter.

The stress redistribution inferred for the Landers earthquake itself increased the stress toward the failure limit for some segments of the San Andreas fault (by up to 10 bars for the San Bernardino Mountain segment and less than one bar for the Coachella Valley segment), but decreased it for the Mojave segment by somewhat less than a bar. Most significantly, it increased the stress toward the failure limit by about 3 bars in the rupture area of the Big Bear quake (M6.5) which occurred 3 hr and 6 min after Landers. We consider the Big Bear quake to be an aftershock of the Landers earthquake because it was within one rupture length of the Landers mainshock and had a magnitude consistent with the normal distribution of aftershock sizes for a M7.5 mainshock.

The local aftershocks of the Landers earthquake have behaved normally for a M7.5 mainshock. The aftershocks in the Landers/Big Bear sequence will continue for at least three years. Table 11 gives probabilities of aftershocks for the combined Landers/Big Bear sequence with magnitudes greater than the specified value for various periods beginning September 1, 1992.

Table 11. Aftershock Probabilities

Magnitude	1 Year Probability	3 Year Probability
>5	85%	95%
>6	23%	34%

The Landers event was followed by a sudden increase in the rate of seismicity over a large area of western United States, particularly in geothermal areas along the Sierra Nevada-Great Basin boundary from Owens Valley to Lake Tahoe and as far north as the southern Cascades. Such widespread distant triggering of earthquakes is largely unprecedented. While the triggering mechanism is not well understood, there is some evidence that dynamic stresses generated by seismic surface waves spreading from the epicenter may be responsible.

To address the prospect for large (M>7) earthquakes in the in the next few years in southern California, some plausible earthquake scenarios have been enumerated, their effects on urban areas of southern California described, and their intermediate-term probabilities estimated. The most likely outcome is that no large earthquake (M>7) will occur within 100 km of the Landers rupture in the next few years. If one should occur it is most likely to originate on one or more of the following structures:

- Miscellaneous faults of the Mojave shear zone, including the Helendale, Lenwood, Old Woman, Springs, northern Johnson Valley, Calico-Blackwater, Rodman-Pisgah, or the southern half of the Emerson fault.
- The San Bernardino Mountains and Coachella Valley segments of the San Andreas fault, or a combination of the San Bernardino Mountains segment with either the Coachella Valley segment or the Mojave segment, or with both.
- The northern San Jacinto fault.

Ground shaking has been simulated for the Landers earthquake and for some of the plausible earthquakes listed above based on existing information about the earthquake source, seismic wave propagation, and geologic site conditions. The simulation yielded a distribution of seismic intensities in general agreement with observations from the Landers earthquake. The high intensity for the epicentral area agrees with levels of damage actually experienced and accelerations as high as 0.9g recorded in the epicentral area. Fortunately such strong shaking only occurred in sparsely populated areas. As shown on the simulated intensity maps, potential events in the Mojave shear zone will have effects similar to the Landers quake. Those on the San Andreas and San Jacinto faults, however, could cause severe shaking in more urbanized areas.

How probable are any of the above plausible earthquakes? According to statistics based on global earthquake catalogs, the probability that a large earthquake (M>7) follows another sharply drops after two months from the occurrence of the first one. Using various formulas, the probability of a large earthquake (M>7) in the greater Landers region was estimated to be 2 to 5 percent within 1 year from September 1, 1992. However, the yearly probability for at least one M7 or larger earthquake somewhere in greater southern California is estimated to be at least 5 percent and up to 12 percent. The larger figures reflects the recent increased seismicity in southern California. The range of values quoted above also allows for the stress redistribution by the Landers earthquake and the ripeness of the southern San Andreas fault.

X. RECOMMENDATIONS

The recommended scientific follow-up to the Phase II report is as follows:

- The new paleoseismic data for the southern San Andreas fault should be incorporated into a revision of probability estimates. For example, these data suggest that the background probability for a large earthquake may be substantially higher than that estimated in 1988, and that the segment boundaries assumed by WGCEP 88 may need revision in order to properly describe the potential rupture zones of large earthquakes.
- The assumptions underlying the methodology used by WGCEP 88 for estimating probabilities of earthquake occurrence must be reexamined.
- Ground motion parameters including peak ground acceleration, duration of shaking, and response spectra for periods of 0.1, 0.3, 1, and 3 sec must be estimated. The existing methodology for calculating these parameters should be validated using the Landers-Big Bear strong motion data and applied to plausible future large earthquakes.
- The probabilities of failure for the numerous major faults in the broader area of southern California need to be estimated. To express the integrated effects of seismic hazard from these faults, a strategy for probabilistic seismic hazard analysis must be developed as soon as possible. It should include the choices of ground motion parameters, mesh size for site conditions, and exceedance probability.
- The regional geotectonic framework of the Landers/Big Bear/Joshua Tree sequence, and any possible tectonic interrelationships between this sequence and other clusters of moderate size earthquakes in the San Gabriel and Imperial Valleys must be considered.

Additional Steps:

- The California Office of Emergency Services should intensify loss reduction and public information efforts (public policy) based on the conclusions of this report.
- The California Office of Emergency Services should plan for a M6 or greater earthquake on the San Andreas fault.

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Appendix
Estimation of Aftershock Probabilities

The aftershock pattern for the Landers and Big Bear earthquakes can be used to estimate the probability of an aftershock occurring in a given magnitude range in a given time period. More than 100 years of observed seismology has firmly established the fact that the frequency of aftershocks decreased as a function of time from the mainshock origin time according to Omori's law,

$$N(t) = \frac{K}{(t+c)^p} \qquad (1)$$

where N(t) is the number of aftershocks per unit time, t is time since the mainshock, and K, c and p are constants which vary from one aftershock sequence to another.

The magnitude distribution follows the Gutenberg-Richter relation for the number of earthquakes of different magnitudes,

$$N(M) = 10^{(a-bM)} \qquad (2)$$

where N(M) is the number of events above some magnitude, M, and a and b are constants.

The parameter K in equation (1) above depends on the magnitude of the mainshock, with larger mainshocks producing more aftershocks. Aftershock data suggest that the "triggering potential" of a mainshock obeys

$$K = 10^{(a'+b\,M_m)} \qquad (3)$$

where a' is a constant, b is the same constant appearing in (2), and M_m is the magnitude of the mainshock. We can combine (1), (2), and (3) to get the rate of aftershock occurrence, $\lambda(t,M,M_m)$,

$$\lambda(t,M,M_m) = 10^{a''+b(M_m-M)}\,(t+c)^{-p} \qquad (4)$$

where a''=a'+a.

The aftershock pattern for the Landers and Big Bear earthquakes can be fit to these equations, yielding the values of the constants given in Table 1. Using these constants, the probability of future damaging aftershocks in this sequence can be computed following the procedures of Reasenberg and Jones (1989), who determined values of a, b, c, and p for many California aftershock sequences. The constants for the Landers/Big-Bear sequence are very close to average values for California earthquakes as shown in the following table.

Knowing the parameters in Omori's Law and the Gutenberg-Richter relation for a particular aftershock sequence allows one to describe the sequence. This description also gives an estimated probability of an aftershock occurring in a given magnitude range in a given time period (see Table 2 in Report).

Aftershock Parameters

Sequence	a	b	c	p
Landers/Big Bear	-1.78	0.85	0.04	0.99
Landers only	-1.97	0.85	0.01	0.90
Big Bear only	-2.60	1.16	0.09	0.93
California average	-1.76	0.90	0.05	1.07